BNFL Inc.

Section 3.1

Hydrogen Generation in the High Level Waste Storage Vessels

BNFL Inc.

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Hydrogen Generation in the High-Level Waste Storage Vessels

3.1.1. Work Identification

This section demonstrates an application of the integrated safety management process to an example of hydrogen generation in the High-Level Waste (HLW) storage vessels V31001A, B, C, D and E. This report focuses on the control of hazards associated with the explosive potential of hydrogen generated by radiolysis.

3.1.1.1. Key Process and Design Parameters

During the operating lifetime of the TWRS-P facility, the HLW Receipt/Storage Vessels V31001A/B/C/D/E will contain hazardous material from several sources in the Hanford Tank Farms. The function of the HLW Receipt/Storage Vessels is to provide storage of washed HLW solids during the first years of facility operation. This provides buffer capacity for the receipt of HLW. The requirement for washed solids is to remove soluble components from the HLW stream and to reduce the sodium concentration fed to the HLW Melter. This reduces the volume of HLW glass produced. Storage is provided to allow early start-up of pretreatment and to reduce tank farm inventory. The storage volume requirement for unwashed solids would be prohibitive.

As discussed further below, from the standpoint of both radiolytic hydrogen generation and radiological dose consequences, the feed from Hanford Tank 241-AZ-101 – following ultrafiltration in the TWRS-P Pretreatment facility – represents the bounding material at risk (MAR) for the hazard addressed in this report.

The early processing feed consists of a combination of Envelope B and Envelope D (Envelope B & D Sludge). Both of these envelopes exist in Tanks 241-AZ-101 and 241-AZ-102. The waste in these tanks consists of supernatant and settled solids. Envelope B is the supernatant (solution) and soluble solids from the settled solids in the tanks. Envelope D is the insoluble settled solids in the tanks.

Tank 241-AZ-101 was picked as the basis for the MAR because it contains the highest concentration of radionuclides of concern.[a] Table 3.1-1 shows the primary radionuclides associated with the solids for each of the Phase I Envelope B & D sludge feed tanks. Table 3.1-1 also lists the mass of washed solids (Envelope D), the percentage of washed solids retrieved, and the resultant maximum amount of washed solids per tank that could be stored in vessels V31001A – E (Elsden 1999).

[a] Strontium-90 (^{90}Sr) is a "radionuclide of concern" because it contributes the highest radioactivity concentration. Americium-241 (^{241}Am) is a radionuclide of concern because it is a major contributor to dose (see Table 3.1-3).

Table 3.1-1. Phase I Envelope B & D Sludge Feed Tanks (Activity Decayed to January 1, 1994)

Tank	^{90}Sr (Curies)	^{241}Am (Curies)	Washed Solids (Kilograms)	Percent Retrieved	Stored Washed Solids (Kilograms)
241-AZ-101	6,360,000	22,600	130,000	90	117,000
241-AZ-102	3,700,000	14,800	222,000	60	133,000
241-AY-102	2,470,000	2,870	N/A	N/A	Combined with 241-C-106
241-C-106	4,770,000	1,120	309,000	85	263,000
241-C-104	630,000	6,700	480,000	100	480,000

Based on the data above, Table 3.1-2 shows the amount of curies of the ^{90}Sr and ^{241}Am per 100 grams solids. As can be seen, Tank 241-AZ-101 has the highest concentration of ^{90}Sr and ^{241}Am (Elsden 1999).

Table 3.1-2. Strontium-90 and Americium-241 Concentration -- Curies per 100 Grams of Stored Washed Solids (Activity Decayed to January 1, 1994)

Tank	^{90}Sr (Ci/100 g)	^{241}Am (Ci/100 g)
241-AZ-101	5.4	0.0193
241-AZ-102	2.8	0.0111
241-AY-102	N/A	N/A
241-C-106	2.8	0.0015
241-C-104	0.1	0.0014

As shown on Figure 3.1-1, the slurry is received from DOE in Vessels V31001A, V31001B, and V31002. The waste is fed from V31001B or V31002 to Vessels V32001 A/B – the ultrafiltration feed vessels. The concentrated solids from the ultrafiltration loop are transferred to Vessel V31001E. From V31001E, the solids are accumulated in the other four vessels V31001A – D, pending vitrification.[b] These solids have been washed to remove soluble species (e.g., Na and Cs) and concentrated for storage.[c]

Pretreatment concentrates the solids either to 20 weight percent for feed to the HLW melter or to 25 weight percent for storage during early processing. 25 weight percent storage was used for this MAR. At that concentration, storage of the Tank 241-AZ-101 activity would require a total slurry volume of 390 m^3 (103,000 gal) (Elsden 1999).

The process requirement is to store all of the washed solids from Tanks 241-AZ-101 and 241-AZ-102. This requirement is satisfied by concentrating the washed solids to 25 wt%. Therefore, it is unlikely that a higher concentration would occur. (**Operating Assumption**)[d]

Table 3.1-3 compares the radiological "dose potential" of the unwashed, unconcentrated solids received from Hanford Tank 241-AZ-101 to those of the washed, concentrated solids stored in vessels V31001A – E. The radioactivity concentrations for "Receipt" are obtained from the Best-Basis Inventory (WHC, 1998a). The radioactivity concentrations for "Storage" represent washing to separate out the cesium inventory, concentration to 25 wt%, and decay to 1 Jan 2006. The dose conversion factors are obtained from EPA 1988. Table 3.1-3 shows that the dose potential of the radionuclides of concern is greater for the "Storage" condition than for the "Receipt" condition. Therefore, storage of washed, concentrated solids from 241-AZ-101 represents the bounding MAR for dose consequences.

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[b] During Part A, the Contract specified that the U.S. Department of Energy (DOE) would transfer washed solids (Envelope D) to the BNFL Inc. facility for processing. The negotiations between the DOE and BNFL Inc. included an agreement to assess early processing of waste as a contract modification (Specification 12), with solids washing occurring at BNFL's facility rather than in DOE's tanks. Furthermore, instead of all operations starting concurrently, this modification includes the pretreatment of the Envelope B and D sludge in Tanks 241-AZ-101 and 241-AZ-102 prior to the start of vitrification operations. Once Envelope B is pretreated to remove soluble radionuclides, the supernatant would be returned to a Double Shell Tank in the Tank Farm for storage. The pretreated solids from washing would be stored in four or more vessels in the TWRS-P facility until High-Level Waste (HLW) Vitrification begins.

As such, the long-term storage of solids with a large inventory of radionuclides was not addressed in the Part A Hazard Assessment. The Part A assessment examined receipt in three vessels of the washed solids from the DOE. At present, the assessment of this process change has added two vessels (of the same design as the HLW Receipt Vessels) to the facility and modified the usage of the Strontium and Transuranic Precipitation Vessel to support this process change. Thus, the number of vessels for receipt and storage of HLW solids has increased (i.e., from three to six).

[c] The washing steps remove soluble chemical species (e.g., sodium) to allow BNFL Inc. to meet contract Specification 8. Washing also removes the soluble radionuclides (e.g., cesium) for feed to the ion exchange system.
If poor washing occurs, Cs could accumulate in these vessels. Since ultrafiltration transfers undergo four or more washes, maloperation during a single wash cycle would be diluted by the other cycles. Continued inefficient washing could occur in pretreatment, but poorly washed solids would either not be sent from ultrafiltration or would have to be returned to the ultrafiltration system because they would not meet the product specification. Thus, the impact of poor washing on the accumulation of Cs is negligible.

[d] The ongoing Research and Technology (R&T) program must demonstrate that the solids concentration can be achieved through ultrafiltration/concentration and that the stored solids can be maintained in suspension by pulsejet agitation.

Table 3.1-3. Comparison of Dose Potential – Received vs. Stored Material at Risk

Radionuclide	*Activity Concentration (Ci/L)*		DCF	*Dose Potential (rem/L)*		
	Receipt	Storage	(rem/Ci)		Receipt	Storage
^{90}Sr	8.1	12	2.39E+05		1.94E+06	2.87E+06
^{137}Cs	5.4	0	3.19E+04		1.72E+05	0.00E+00
^{241}Am	0.038	0.058	4.44E+08		1.69E+07	2.58E+07
				Totals	1.90E+07	2.86E+07

Table 3.1-4 presents a similar comparison with respect to the potential for radiolytic hydrogen generation. Using the radioactivity concentrations in Table 3.1-3 and the total energy per disintegration (dis) from Lindquist 1999a and DHEW 1970, Table 3.1-4 shows that the energy deposition rate per liter (due to both beta/gamma and alpha radiation) is slightly greater in the stored configuration than in the received configuration. Since the radiolytic hydrogen generation rate is directly proportional to the energy deposition rate, the stored, washed solids represent the bounding MAR for purposes of hydrogen generation.

Table 3.1-4. Comparison of Hydrogen Generation Potential - Received vs. Stored Material at Risk

			Energy Deposition Rate (MeV/s/L)			
	Total Energy (MeV/dis)		**Receipt**		**Storage**	
Radionuclide	$\beta\gamma$	α	$\beta\gamma$	α	$\beta\gamma$	α
^{90}Sr	1.131	0	3.39E+11	0.00E+00	5.02E+11	0.00E+00
^{137}Cs	0.7577	0	1.51E+11	0.00E+00	0.00E+00	0.00E+00
^{241}Am	0	5.42555	0.00E+00	7.63E+09	0.00E+00	1.16E+10
Totals			4.90E+11	7.63E+09	5.02E+11	1.16E+10

Therefore, use of the washed, concentrated solids provides the bounding assumptions for both radiolytic hydrogen generation and dose consequences.

3.1.1.1.1. Detailed Process Description

The following process description expands upon the summary discussion above. It is applicable only to the first years of pretreatment (i.e., the pretreatment of the contents of AZ-101 and AZ-102). After the first years of operation, the HLW melter operates at capacity to work off the solids backlog from pretreatment. Thus, the largest stored inventory of radionuclides will occur during the pretreatment period. In subsequent years, the HLW sludges will require limited storage prior to processing in the HLW Melter.

Receipt of HLW Feed from the DOE

Document RPT-W375HV-TE00001, *HLW Pretreatment in Accordance with Specification 12* (BNFL Inc. 1998e), outlines the preferred configuration for the receipt and treatment of HLW feed, as summarized below. The initial batch of HLW feed from the DOE (600 m^3 or 159,000 gal) is received by the pretreatment facility into the Envelope D Receipt Vessels V31001A and V31001B (225 m^3 or 59,4000 gal) and into the Strontium/TRU Precipitate Vessel V31002 (225 m^3 or 59,400 gal). After this initial batch, transfers will be limited to between 200 and 400 m^3 (52,800 and 106,000 gal) each.

The contents of V31001A will need to be transferred to V31001B before being fed to the ultrafilters, because there is no route from V31001A to the ultrafiltration feed vessels. V31001A and B may continue to serve as feed receipt tanks until they are required to be used for lag storage of the pretreated solids. Once V31001A and B have filled, subsequent batches of 200 m^3 (52,800 gal) each will be fed to the Sr/TRU precipitation vessel V31002 during the first years of operation. (Both V31002 and V31001B serve as ultrafilter feed tanks.)

<u>Lag Store HLW Solids</u>

Pretreated HLW slurry will be transferred to V31001E for storage or transferred to the remaining available storage vessels V31001A/B/C/D. Vessel 31002 is used for receipt only.

Solids from ultrafiltration are routed to V31001E in batches of up to 70 m^3 (18,500 gal) each. The actual size of the batch will depend on the starting solids content of the ultrafilter feed and on the effectiveness of the water washing and/or caustic washing operations. Once V31001E becomes full, the solid slurry is transferred to either V31001C or V31001D. From these vessels, the slurry can only be transferred back to V31001E or to V31001B (from V31001C) or to V31001A (from V31001D). The order of vessel filling is postulated to be V31001A, V31001D, V31001B, V31001C, and finally V31001E. On average, each vessel will contain approximately 200 m^3 (52,800 gal) of 25 weight percent HLW solids at the end of this early pretreatment operation.

3.1.1.1.2. Design Parameters

The key baseline design parameters for the HLW vessels are as follows (BEL 1997):

Total volume	=	285 m^3 (75,300 gal)	
Overflow Volume	=	235 m^3 (62,100 gal)	(84% of total)[e] (**Design Assumption**)
Maximum Operating Capacity	=	225 m^3 (59,400 gal)	(80% of total)
Operating Volume	=	197 m^3 (52,000 gal)	(70% of total)
Material of Construction	=	SS 304L	
Head/Shell Thickness	=	16 mm (0.63 inch)	

The material of construction for storage vessels was selected based on its ability to resist corrosion and erosion and to provide continued service over the useful design life of the TWRS-P facility.

The HLW storage vessels are all equipped with cooling capability to facilitate temperature control. At a minimum, tank contents are monitored for level and temperature. All process nozzles exit or enter from the top of the tank (no side penetrations).

The number of reverse flow diverters (RFDs) in a particular vessel is determined by transfer requirements. Each vessel is equipped with mixing capability (pulsed jet mixers). The number of mixers

[e] The overflow volume is not specified in the Mechanical Data Sheet for the HLW vessels (BEL 1997), but rather was identified during the hazard evaluation for this worked example.

employed will be adequate to ensure complete mobilization of the solids. Low maintenance pulsed jet mixers and RFDs are employed to minimize radiation exposure to workers and downtime.

Pneumercators provide liquor level measurement.

3.1.1.2. Interfaces

The upstream process feed to the HLW Receipt/Storage Vessels is from HLW pretreatment. The downstream process is Feed Blending prior to feeding to the HLW Melter.

The interface between HLW solids storage and ultrafiltration requires that ultrafiltration:

- Separate the liquid from the solids (Envelope D)
- Wash (water or caustic) the separated solids.

The stored solids are blended with separated radionuclides (e.g., Cs and Tc) and glass formers prior to being fed to the melter.

The vapor spaces of all the TWRS-P process vessels, including the HLW storage vessels, are vented to the Process Vessel Ventilation System (PVVS). Multiple vessels discharge through the PVVS through a common header.

3.1.1.3. Operating Environment and Setting

There are two cells in the Pretreatment Building, each containing three HLW Receipt/Storage Vessels. The south cell contains vessels V31001C, D, and E; its volume is approximately 155,400 ft^3 (4400 m^3). The north cell contains vessels V31001A and B and V31002; the volume of the south cell is considerably larger (233,000 ft^3 or 6600 m^3) (BNFL Inc. 1998g).

There are no electrical or instrumentation and control (I&C) components located within the cell; however, there are I&C components located outside the cell that communicate (through instrumentation lines) with the potentially explosive atmosphere in the vessel.

The C5 Extract System provides a continuously filtered exhaust from the process cells enclosing the HLW receipt/storage vessels.

Due to radioactivity in the storage vessels, the cells will be inaccessible to personnel. The vessels will operate at atmospheric pressure. Although the aqueous solution in the vessels will be at an elevated temperature due to decay heat, the vessels are cooled; therefore, the cell temperature should be only slightly higher than temperature in the operating gallery.

3.1.1.4. Applicable Experience

Hydrogen generation by radiolysis is a hazard inherent in processing and storing highly radioactive aqueous waste slurries. BNFL has extensive experience in these types of operation. BNFL has successfully controlled radiolytic hydrogen in reprocessing facilities at Sellafield (e.g., THORP), HLW vitrification facilities, the Site Ion Exchange Plant (SIXEP), intermediate level waste (ILW) encapsulation plants such as EP1 and EP2, HLW and ILW waste storage facilities such as B30 and B38, and laboratories.

BNFL uses four main approaches to manage those hydrogen hazards that cannot be eliminated by design:

1. The traditional approach for controlling hydrogen concentrations in large scale facilities typically involves extracting air from the cell through the vessel to a filtered exhaust cleanup system similar to the TWRS-P Process Vessel Ventilation System (PVVS), prior to discharge through a stack. Two examples are SIXEP and B38. SIXEP contains four 1000 m^3 (264,000 gal) tanks that contain either spent ion exchange material or sludge from corroded fuel cladding. Hydrogen generation is low because it is generated by radiolysis and is reasonably well distributed across the 11-m (36-ft) diameter tanks. Therefore, the vessel ventilation flowrate is low. B38 consists of several silos, each of which contains 600 m^3 (21,200 ft^3) of fuel cladding stored under water. Hydrogen generation by radiolysis is insignificant compared to that by corrosion of the magnesium cladding. Hence, the airflow rate across the silo vapor space is approximately 200 cfm (340 m^3/h) to ensure hydrogen cannot build up in any part of the vapor space. More than 1000 m^3 (35,300 ft^3) of waste has been retrieved from B38 and successfully encapsulated in concrete in EP1 and EP2 to date. Also, EP1 and EP2 plants take material for encapsulation from reprocessing plants and have significant throughputs. For example, EP1 handles the cladding from 1,500 tonne (1,650 ton) of Magnox fuel each year. Hydrogen control in all three plants has been successful.

2. Inert atmospheres are used to manage situations in which the hydrogen generation rate is unpredictable. The major plant at Sellafield that uses inert gas is B38. In some circumstances, hydrogen production due to corroded fuel cladding corrosion can increase considerably. In order to have sized a PVVS at B38 to cater for increased hydrogen production, a large margin would have been required to account for uncertainties, which would have led to a costly solution for normal operation. Therefore, nitrogen inerting was selected. The system comprises N_2 storage tanks, an air liquefaction plant, and a separate extract facility. The extract facility has a total capacity of 3500 cfm (5,950 m^3/h).

3. Hydrogen getters (i.e., materials that scavenge hydrogen) are used to control hydrogen buildup in sealed spaces, such as shipping casks, where it is impractical to employ forced air purging or inerting. Therefore, BNFL's UK experience is not applicable to the TWRS-P HLW vessels because of differences in container types and materials contained therein.

4. More recently, BNFL has adopted passive venting of tank vapor spaces to control hydrogen concentrations, as discussed below.

One example of using passive venting is the centrifuge cake tanks in the Waste Encapsulation Plant (EP2) at Sellafield. Although the EP2 vessels are very much smaller than those proposed for TWRS-P, the continuous specific hydrogen generation rate in EP2 is a factor of 4.5 higher than in TWRS-P, and the continuous hydrogen release rate per unit surface area of liquor in EP2 is approximately 25% higher than in TWRS-P. Finally, the time required for the EP2 vessel vapor space hydrogen concentration to increase from zero to the lower flammability limit (LFL) is roughly comparable to the time calculated for TWRS-P (assuming a sealed vessel). Table 3.1-5 below summarizes the comparison.

Table 3.1-5. Comparison of Sellafield EP2 and TWRS-P Vessel Parameters

	EP2 Centrifuge Cake Vessel	Proposed TWRS-P Receipt Vessel

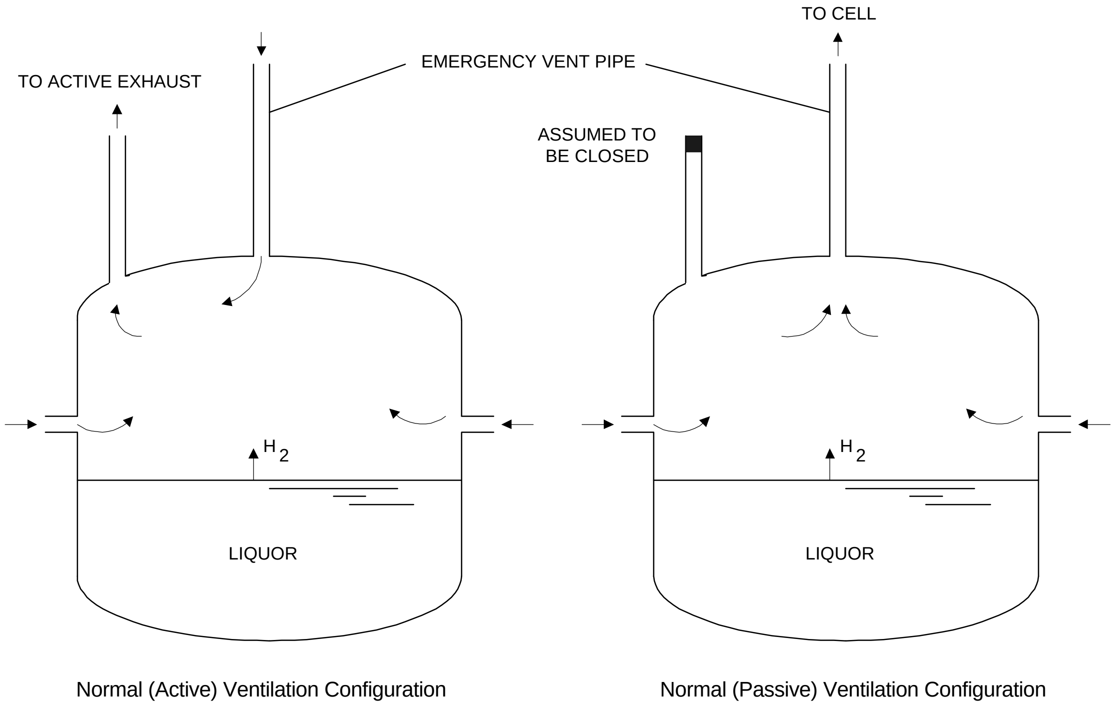
	EP2 Centrifuge Cake Vessel	**Proposed TWRS-P Receipt Vessel**
Total volume	17.7 m^3 (4680 gal)	285 m^3
Normal liquor volume	10 m^3 (2640 gal)	197 m^3
Normal vapor space volume	7.7 m^3 (2030 gal)	88 m^3
Hydrogen generation rate	0.015 m^3/h (0.53 ft^3/h)	0.078 m^3/h (2.8 ft^3/h)*
Specific hydrogen generation rate (per unit volume of liquor)	1.5 E-3 L/h/L (2.0 E-4) (ft^3/h/gal)	3.3 E-4 L/h/L (4.5 E-5 (ft^3/h/gal)
Surface area of liquor	4.8 m^2 (52 ft^2)	33.2 m^2 (357 ft^2)
Hydrogen release rate at liquor surface per unit area	3.1 L/h/m^2 (0.077 gal/h/ft^2)	2.4 L/h/m^{2*} (0.058 gal/h/ft^2)
Time to LFL if vessel sealed	20 hours	26 hours*

* At overflow volume of 235 m^3 (62,100 gal;); see Section 3.1.1.1.3.

EP2 employs a passive ventilation system in conjunction with an active ventilation system to control the concentration of H_2. The passive system uses the buoyancy of H_2 to vent the vessel following the loss of power. Through well-proven buoyancy calculations, BNFL has demonstrated the viability of the EP2 passive vessel vent system. More detailed Computational Fluid Dynamics (CFD) models are now available that can be used, when necessary.

BNFL continues to develop its CFD modeling capability and has an ongoing program with the UK Nuclear Installations Inspectorate (NII) to refine and validate the computer codes. Also, BNFL has conducted testing with scaled mock-ups to further validate the computer models that demonstrate the effectiveness of the passive ventilation. This experience and technology can be used in the development of highly reliable passive systems for the TWRS-P facility.

The following figure is a schematic illustrating operation of the EP2 active and passive vessel ventilation systems.



3.1.2. Hazard Evaluation

3.1.2.1. Hazard Identification

Hydrogen is evolved by radiolysis in aqueous radioactive wastes. Given sufficient concentrations, mixtures of hydrogen and air can burn or explode violently if ignited, posing obvious hazards. Common practice throughout industry, as reflected in NFPA 69, is to limit accumulation of hydrogen in air to less than ¼ of the Lower Flammability Limit (LFL) of 4% hydrogen by volume, which is below the minimum concentration required to support combustion (CRC 1974). This industry practice has been adopted by TWRS-P for normal operation (Fairclough 1998).

The HLW storage vessels represent a potential explosive hazard in terms of total volume of flammable gas, material at risk and the time required to reach a hazardous condition. These vessels were chosen for the example presented in this report, recognizing that this assessment is not intended to bound all hydrogen hazards (Edwards 1998).

3.1.2.1.1. HLW Storage Vessel Hazard Characterization

The hydrogen hazard associated with an HLW storage vessel was characterized by estimating:

- the hydrogen generation rate

- the corresponding time requirements to reach flammable concentrations in the vessel head space
- the minimum dilution air required to maintain hydrogen concentrations below 25% of the lower flammable limit (LFL).

Lindquist (1999a) estimates the hydrogen generation rate in HLW vessels V31001C, D and E. The radioactivity content of tanks 241-AZ-101 and 241-AZ-102 was obtained from WHC 1998a and WHC 1998b, Tables D4-22 and E4-23, respectively. This radioactive inventory was corrected for radioactive decay that will have occurred before the HLW vessels receive initial feed (to January 1, 2006).

Vessel V31001C is assumed to be 83.5% full (overflow volume) of washed solids from Hanford tank 241-AZ-101 (**Design Assumption**). The remainder of the 390 m^3 (103,000 gal) of the contents of tank AZ-101 is assumed to be contained in vessel V31001D. Vessel V31001E is assumed to be 83.5% full of washed solids from Hanford tank 241-AZ-102. Although BNFL Inc. does not anticipate that TWRS-P will store HLW washed solids in this configuration (see Section 3.1.1.1.1), this set of assumptions is bounding for the purpose of determining hydrogen generation rate in any single HLW storage vessel.

Based on the process description (Section 3.1.1.1.1), the bounding hydrogen generation rate from a single HLW storage vessel is obtained by assuming that the vessel is filled to the overflow with washed solids from Hanford tank 241-AZ-101 (**Design Assumption**). The bounding concentration of solids in the HLW storage vessels is 25 wt% (**Design Assumption**).

The alpha, beta and gamma energy spectra for this inventory were obtained from the *Radiological Health Handbook* tables (DHEW 1970). The analysis conservatively assumes that all of the energy from the radioactivity is deposited in the vessel water (i.e., not in the solids). The total energy deposition rates determined for the three vessels that were analyzed are listed below:

	Beta/Gamma	**Alpha**
V31001C	1.20E+17 MeV/s	2.79E+15 MeV/s
V31001D	7.94E+16 MeV/s	1.84E+15 MeV/s
V31001E	6.20E+16 MeV/s	1.68E+15 MeV/s

Lindquist 1999a uses the following radiolytic hydrogen yields ("G values") for pure water:

β/γ: 0.45 molecules/100 eV (RHO 1985)
α: 1.57 molecules/100 eV (Spinks and Woods 1976)

The results of the hydrogen generation calculation are shown in Table 3.1-6.

Table 3.1-6. Hydrogen Generation Parameters for Vessel V31001C/D/E[f]

Parameter	**V31001C**	**V31001D**	**V31001E**
Hydrogen generation rate	2.8 ft^3/h	1.8 ft^3/h	1.4 ft^3/h

[f] Based on an assumed overflow collection connection to the HLW vessel at 235 m^3 (62,100 gal) (83.5% full) (**Design Assumption**).

Time to reach 25% LFL* (1% vol. H_2)	6.4 h	25.3 h	12.3 h
Time to reach LFL* (4% vol. H_2)	26 h	103 h	50 h
Dilution air required to maintain less than 25% LFL – the upper allowable concentration for normal operation	> 4.6 ft^3/min	> 3.0 ft^3/min	> 2.4 ft^3/min

* Assumes obstructed vent path and no dilution air (i.e., from pneumercators)

Other Potential Sources of Hydrogen

The solids in the HLW storage vessels are in a slurry with 0.1M NaOH. In general, the solids are resistant to dissolution by nitric acid alone. The other process chemicals used in this portion of the facility include those for the precipitation of Sr and TRU, e.g., $Sr(NO_3)_3$, $Fe(NO_3)_2$, and NaOH. The inadvertent addition of any of these chemicals would either suppress H_2 (in the case of the nitrates) or increase the free hydroxide concentration. Any organic chemicals present in the feed stream will have been removed during washing before the slurry is transferred to the HLW storage vessels; consequently, organics will not contribute to hydrogen generation. Thus, production of hydrogen due to corrosion of either the vessel or its contents or due to inadvertent addition of process chemicals would not be significant.

The solids in Tanks (241-) AZ-101 and (241-) AZ-102 were generated from processing N Reactor Fuel between 1983 and 1989. These solids resulted from the neutralization of waste from the High Activity Waste (HAW) stream prior to discharge to the tanks. The majority of the solids consist of the process chemicals and the corrosion products from the PUREX Plant's stainless steel process equipment. Thus, further corrosion of solids in the HLW storage vessels will be minimal. Therefore, potential hydrogen generation due to corrosion of solids is considered to be negligible.

The possibility of a sudden, episodic release of hydrogen that has been trapped in the sludge requires further evaluation (**Open Issue**; see Section 3.1.6.3).

The hydrogen generation parameters listed in Table 3.1-6 indicate the need for further hazard evaluation and development of a control strategy.

3.1.2.2. Event Sequence

Hydrogen is continually generated in the HLW process vessels. There are no known sources of ignition in the vessel or the connecting ventilation system. However, because the energy required to ignite a flammable mixture of hydrogen in air is low (such as might be produced by metal striking metal or even gas friction), the possibility of ignition is assumed.

The vessel and ventilation ducting geometry indicate that a postulated hydrogen ignition would take the form of a deflagration. However, the design of connecting piping and instrumentation currently provides insufficient detail to justify excluding a detonation; therefore, detonation has been assumed (**Open Issue**; see Section 3.1.6.3).

3.1.2.3. Unmitigated Consequences

Unmitigated dose consequences for two possible types of hydrogen explosions are assessed in the following subsections.

3.1.2.3.1. Detonation Assessment

To estimate the potential unmitigated consequences of a hydrogen explosion, a calculation was developed to examine ignition of a stoichiometric mixture of 29.6% (volume) hydrogen in the vapor space of the vessel (Lindquist 1999b). This amount of hydrogen yields the maximum possible explosion energy. The analysis used an aerosol production mechanism that is conservative but typical of what would be expected from a detonation inside a closed vessel (BNFL plc 1997). The total amount of aerosol formed is proportional to the vapor space volume; therefore, the most conservative dose consequences would occur when the vessel is nearly empty. This is the basis used in the dose consequences analysis (Lindquist 1999b).

The key assumptions used in calculating severity levels for the hydrogen detonation are as follows:

- The material at risk, i.e., the assumed radionuclide inventory, is based on chemical species assumed to remain after washing of 241-AZ-101 waste (Lindquist 1999a).
- The explosion of the flammable gases produces a maximum respirable radioactive aerosol concentration of 1 g/m^3 in the tank vapor space. The concentration of radioactivity in the aerosol is assumed to be the average concentration of radioactivity in the vessel. This is a conservative assumption, because the radionuclides are associated with the suspended solids in the vessel, not with the liquid.
- One g/m^3 aerosol loading in the tank vapor space (BNFL plc 1997). This loading is used in the detonation analysis and is bounding for the deflagration analysis.
- The vapor space available for aerosol loading is assumed to be the full volume of the tank.
- The pressure rise in the tank from the hydrogen burn causes the tank to fail.
- Total burden of radioactive aerosols from the tank vapor is dispersed in the cell volume, resulting in 106 mg/m^3 suspended aerosols. The facility worker is exposed to the resulting concentration.
- The aerosol-laden air from the process cell exits the building with no depletion (conservative assumption for the co-located worker and the public).
- The facility worker is assumed to be exposed to the resulting concentration for a maximum of ten minutes, which is considered bounding for the following reasons:
  - The worker is considered to be immersed in the aerosol at the peak concentration of 106 mg/m^3 for the entire duration. In reality, the “cloud” would dissipate rapidly due to condensation, plateout, and dispersion.
  - The explosion and the mist produced by the saturated water vapor in the cloud at the assumed concentration would alert the worker to evacuate the vicinity.

The dose consequences reported in Table 3.1-7 represent maximum hypothetical doses to be used to establish severity levels. The dose consequence assessment did not consider the potential of the vessel to contain the explosion. Since the potential effects of detonation or deflagration on the cell structure have not been analyzed, no credit is taken for the inherent mitigation that would be provided by the massive reinforced concrete walls and roof of the facility.

Other potential sources of aerosol generation include the effects of splashed liquid falling from the vessel, long term resuspension from the pool of spilled liquor and the release of the radioactive material contained in HEPA filters within the vessel ventilation system. The combined contribution of these sources did not significantly increase the calculated dose from the aerosol generated by the explosion (Lindquist 1999b).

Table 3.1-7. Unmitigated Dose Consequences[a]

Population	**Dose (rem)**
Facility Worker	530
Co-located Worker	27
Public	0.04

[a] Worst pathway via inhalation

3.1.2.3.2. Deflagration Assessment

At this stage of the design, it is appropriate to make a very conservative assumption that a hydrogen detonation is possible. However, BNFL experience with hydrogen generation in vessels with designs similar to the TWRS-P design indicates that is likely that the geometry of the TWRS-P tanks and piping will not support a transition from deflagration to detonation. If this can be demonstrated for the TWRS-P HLW storage vessels, then the potential unmitigated consequences of hydrogen ignition would be significantly lower than those presented above for detonation. The potential doses resulting from a deflagration are evaluated below.

The unmitigated consequences from a deflagration are estimated for two possible, alternative conditions:

- The deflagration does not breach the HLW storage vessel and associated piping
- The deflagration results in a release to the process cell.

Under the first condition, any aerosol generated by the deflagration would be vented to the atmosphere via the PVVS. Based on recommendations in the Sellafield database (BNFL plc 1997), a deflagration would produce an aerosol concentration of 100 mg/m^3 in the vessel vapor space. Thus, the release from a deflagration to the vessel vapor space would be 10% of the release postulated for the detonation (1 g/m^3). Based on the consequences from the detonation, the release from a deflagration would translate to the following consequences:

- 2.7 mrem to the co-located worker, which is well below the SL-3 limit
- 0.004 mrem to a member of the public, which is well below the SL-4 limit
- The potential consequence to the facility worker would be insignificant, because there would be no release to the operating gallery

Under the second condition, any release to the cell from the deflagration also would be less than 10% of the release postulated for the detonation. Based on the dose consequences from the detonation, the release from a deflagration would result in a dose of 53 rem to the facility worker, assuming no decontamination factor (DF) across the fabric of the cell. However, the *Sellafield Release Fraction Data Base* (BNFL plc 1997) recommends a DF of 10 for pressurized cells with penetrations. Applying this DF to the process cell results in a dose of 5.3 rem to the facility worker. Therefore, a deflagration would result in SL-2 consequences to the facility worker, at worst. The consequences to the co-located worker and the public would be no larger than for the first condition (i.e., SL-3 and SL-4, respectively).

The evaluation presented above shows that the potential consequences from a detonation are very much larger than the potential consequences from a deflagration. Since it is unlikely that the design will produce conditions that would be capable of promoting hydrogen detonation, the unmitigated consequences from potential hydrogen accumulation postulated in this example may be overly conservative. Therefore, the credibility of a hydrogen detonation in TWRS-P will be reevaluated as the design progresses (**Open Issue**; see Section 3.1.6.3).

3.1.2.3.3. Consequences Summary

In summary, the unmitigated consequences and severity levels that form the basis for development of the control strategy are shown in Table 3.1-8.

Table 3.1-8. Unmitigated Dose Consequences and Severity Levels[a]

Population	Dose (rem)[a]	Severity Level
Facility Worker	530	SL-1
Co-located Worker	27	SL-1
Public	0.04	SL-4

[a] Based on detonation.

3.1.2.4. Frequency of the Initiating Event

Since a flammable concentration of hydrogen will eventually develop in the vessel vapor space if the hydrogen is not removed, the "initiating event", *per se*, is the introduction of hydrogen producing material into a closed process vessel. It is conservatively assumed that, once a flammable concentration of hydrogen exists, the hydrogen will ignite. Therefore, the frequency of the accident is equal to the unreliability of the control strategy expressed on an annual basis.

3.1.2.5. Common Cause and Common Mode Effects

The selected control strategy must account for all credible common cause and common mode effects. This requirement will be verified in the evaluation of the selected control strategy (Section 3.1.5.1). No common cause or common mode effects were identified as being likely contributors to accident frequency.

3.1.2.6. Natural Phenomena Hazards and Man Made External Events

Natural phenomena hazards (NPH) are discussed on a facility-wide basis in Section 2.10 (**Design Assumption**). Since seismic events could lead to high hydrogen concentrations by causing failure of those systems that remove the generated hydrogen, the selected control strategy must ensure that hydrogen can be vented after an earthquake (**Safety Function**).

Similarly, man-made hazards are discussed on a facility-wide basis in Section 2.10. There are no man-made hazards that affect this strategy uniquely. Therefore, man-made hazards are not addressed specifically in this example.

3.1.3. Control Strategy Development

3.1.3.1. Controls Considered

The control strategy options proposed for initial consideration during the process design phase included:

1. Provide an inert gas blanket. The tank vapor space could be kept full of an inert cover gas, such as nitrogen or carbon dioxide.

2. Add inhibitors to vessel contents to suppress radiolysis. It is known that nitrate ion will inhibit the production of radiolytic hydrogen. If the concentration of these species were kept at a high-level in the tank, the hydrogen hazard would be effectively neutralized.

3. Dilute with forced purge air and vessel ventilation. The production of hydrogen can be offset by the injection of dilution air into the vapor space. This option would require an operating vessel ventilation system to maintain the negative pressure differential between the cell and the vessel.

4. Provide passive vessel vent using passive air inbleed. Vent pipes could be added to the vessel that would utilize the natural buoyancy of hydrogen and the thermal gradient between the vessel and cell to circulate air through the tank vapor space.

5. Provide active vessel ventilation with air inbleed. Similar to the purge air option, this option would "suck" dilution air into the vapor space through vent pipes added to the vessel.

6. Eliminate sources of ignition. All conducting surfaces in potential contact with radiolytically generated hydrogen would be properly grounded. All electrical equipment in potential contact with hydrogen would be rated for service in potentially explosive environments.

7. Design tank as a pressure vessel. The tank could be designed to withstand the effects of an explosion.

8. Install hydrogen getters. Material could be installed in the tank vapor space that would react with the hydrogen to form stable chemical compounds, thus preventing a buildup of free hydrogen.

9. Install hydrogen igniters. Igniters (i.e., glow plugs) could be installed in the vapor space to recombine the hydrogen with the oxygen in the air as it the hydrogen is formed, thus preventing a buildup of free hydrogen.

10. Install catalytic recombiners in the vapor space. Recombiners could be installed in the vapor space to recombine the hydrogen with the oxygen in the air as the hydrogen is formed, thus preventing a buildup of free hydrogen.

3.1.3.2. Control Strategy Selection

Control strategy selection was conducted in a two-step process: first, clearly unrealistic control elements were deleted and, second, engineering tradeoffs were considered to further down-select the options.

3.1.3.2.1. Step 1 (Initial Screen)

The merits of each of the potential controls described above were considered, primarily against the following set of criteria:

- Effectiveness
- Practicability
- Reliability
- Demonstrability
- Compliance with laws and regulations
- Ability to comply with DOE/RL-96-0006, *General Radiological and Nuclear Safety Principles* (in particular, use of proven engineering practice, ease of providing inherent/passive safety features, radiation protection features, and avoidance of undue reliance on human actions).

The objective of this review was to identify the main advantages and disadvantages of each of the controls and to eliminate any controls that were not considered viable. The results of the evaluation are summarized in Table 3.1-9.

Table 3.1-9. Initial Evaluation

Control	Advantages	Disadvantages	Compliance with Top-Level Principles	Further Consideration in Control Strategy
1. Inert Gas Blanket	Minimizes potential of forming flammable atmosphere	Presents asphyxiation hazard; difficult to demonstrate the required reliability for SL-1	Yes	Yes
2. Add Inhibitors to Vessel Contents (nitrate ions will inhibit radiolytic H_2 evolution)	Reduces rate of generation of hydrogen to insignificant levels	Impractical due to detrimental effect on process (e.g., nitrate ion would have to be removed prior to melter)	Yes	No
3. Dilute with forced purge air and vessel ventilation	Effective/practicable: eliminates flammable atmosphere Demonstrable - proven technology	Requires monitoring and control of purge air flow. Difficult to demonstrate the required reliability for SL-1	Yes	Yes
4. Passive Ventilation to Cell	Effective/Practicable - eliminates flammable atmosphere. Demonstrable -- proven technology; inherently passive system, tolerant of a wide range of conditions	Requires penetration in vessel (i.e., establishes communication between vessel and cell); this will increase the necessary ventilation exhaust capacity required to minimize spread of radioactivity On-line detection of failure of system (e.g., plugged vent path or excess) is difficult Requires that cell be vented	Yes	Yes

Table 3.1-9. Initial Evaluation

Control	Advantages	Disadvantages	Compliance with Top-Level Principles	Further Consideration in Control Strategy
5. Vessel vent extract with passive air inbleed	Effective/practicable - eliminates flammable atmosphere Demonstrable - proven technology	Difficult to achieve the required reliability for SL-1 Establishes communication between vessel and cell(see No. 4)	Yes	Yes
6. Eliminate sources of ignition	Minimize potential for explosion	Hydrogen has extremely low ignition energy; therefore, this option, by itself, is not demonstrable or effective	Yes	No[g]
7. Design tank as pressure vessel	Consequences of H_2 explosion are minimized	Impractical - very difficult to design as pressure vessel because of number of required penetrations Connecting piping and instrument lines would also need to withstand explosion overpressures	No –- By itself, may violate Defense in Depth subprinciples of Prevention and Control, because hydrogen explosions are more likely	No
8. Hydrogen getters	Passive safety; - eliminates flammable atmosphere	Difficult to demonstrate that long-term performance is acceptable in this environment, thus, not reliable.	No -- No proven engineering practice in this environment. Addition or replacement of getters would challenge ALARA top-level principle	No

[g] Although Option No. 6 is not carried forward to Step 2 of the control strategy selection process, practices and design provisions to minimize sources of ignition will be implemented for defense in depth.

Table 3.1-9. Initial Evaluation

Control	Advantages	Disadvantages	Compliance with Top-Level Principles	Further Consideration in Control Strategy
9. Igniters	Passive safety, if energized by DC power Eliminates potentially explosive atmosphere	Vapor space hydrogen concentration will contain flammable mixture Difficult to demonstrate that long-term performance is acceptable, thus possibly unreliable	Unlikely - No proven engineering practice in this environment. Maintenance/replacement would challenge ALARA top-level principle May violate Defense in Depth subprinciples of Prevention and Control	No
10. Catalytic Recombiners	Passive safety. Eliminates potentially explosive atmosphere	Difficult to prove long term performance is acceptable. In this environment, difficult to monitor/verify performance	Unlikely - No proven engineering practice in this environment. Maintenance/replacement would challenge ALARA top-level principle May violate Defense in Depth subprinciples of Prevention and Control	No

As noted in Table 3.1-9, Options 2, 7, 8, 9, and 10 were rejected. The rationale for rejecting each option is explained further below.

- Addition of nitrate to the tank as a hydrogen inhibitor was rejected because it is impractical. Nitrate addition would be detrimental to the process, because nitrates would have to be removed from the HLW stream to meet vitrification feed specifications. Alternatively, nitrous oxide removal equipment would have to be added to the melter offgas to meet environmental release standards. Thus, addition of nitrate would introduce an additional processing step and require additional equipment and space.

- Designing the tank as a pressure vessel capable of withstanding a detonation was rejected because of the large number of piping connections to the vessel. While a pressure vessel could be designed to contain the overpressure from a detonation, it would not be practical to also provide piping connections capable of withstanding the detonation. In addition, even if the radiological consequences were minimized, a detonation in a process vessel would impact operations and present an unacceptable commercial risk. The resultant replacement of the damaged vessel and piping in the process cell environment would be very difficult, necessitating an extended outage. Therefore, this option is impractical.

- Provision of hydrogen getters was rejected because it would be difficult if not impossible to guarantee adequate performance over the life of the tank. After startup, it would be impractical to add or replace hydrogen getters. Furthermore, addition or replacement of hydrogen getters would challenge top-level principle 4.2.3.2 of DOE/RE 1998, "Radiation Protection Features," with respect to maintaining occupational radiation exposures ALARA.

- Provision of hydrogen igniters was rejected because it would be difficult to guarantee the igniters for the service life of the vessel. Replacement of igniters in the vessel would be impractical. Furthermore, replacement or maintenance of igniters would challenge top-level principle 4.2.3.2 of DOE/RE 1998, "Radiation Protection Features," with respect to maintaining occupational radiation exposures ALARA. Finally, because igniters operate by burning hydrogen, a flammable mixture would always exist in the vessel vapor space; this would violate standard BNFL hydrogen control safety practices (Fairclough 1998).

- Catalytic recombiners were rejected because their in-service reliability is relatively low and recombiners themselves present explosive hazards. As such, in-vessel recombiners would not be acceptable. In-cell recombiners would present maintenance problems because of the lack of access to the cell. An out-of-cell recombiner system would complicate the design and, as noted above, would not completely remove the explosive hazard.

The remaining potential controls, as described below, were carried forward for further evaluation.

- An inert gas blanket to displace O_2 from the vessel vapor space.

- An active vessel ventilation system that removes hydrogen from the vessel vapor space using bleed-in air from the cell and the vessel ventilation fans as the motive force.

- An active air purge system to inject dilution air into the vessel vapor space with exhaust provided by the active vessel ventilation exhaust.

- A passive vent system that removes hydrogen from the system using hydrogen's natural buoyancy and the thermal gradient between the vessel and the cell as the motive force.

Because the energy required to cause ignition of a flammable mixture of hydrogen in air is so low, it is difficult to completely eliminate all ignition sources. Therefore, as a single control strategy, eliminating ignition sources is not practicable. However, practices to minimize ignition sources will be implemented for defense in depth.

The controls carried forward to Step 2 all focus on preventing potentially explosive concentrations of hydrogen in the HLW storage vessels. This focus results from both safety and commercial considerations:

- The overpressure from a major detonation in HLW storage would severely challenge both of the confinement barriers, namely the process vessel and the cell structure.

- The cost from downtime and repairs after a detonation would be unacceptable even if the radiological consequences from the event could be tolerated.

3.1.3.2.2. Step 2 (Engineering Screen)

These options were then further developed through an engineering "trade study" type review that took into account the following considerations to ensure a comprehensive approach in the context of other hazards and the overall design:

- Introduction of secondary hazards
- Impact on safety features provide to protect against other hazards
- Impact of other hazards on the control strategy
- Robustness to other fault conditions and environments (including seismic and other design basis events)
- Preference for passive over active, and, if active, automatic over administrative/procedural
- Robustness of any administrative controls required
- Cost
- Operability
- Maintainability
- Ease of justification (e.g., consistency with proven technology).

These considerations are presented in Table 3.1-10.

Table 3.1-10. Hydrogen Hazard Engineering Evaluation

Criterion	Inert Vapor Space	Active Vessel Ventilation (Bleed-In Air Supply)	Active Air Purge & Exhaust	Passive Vessel Vent
Introduction of Secondary Hazards	Asphyxiation hazard to workers	Spills to cell if vessel overflow cannot cope with fill rate Increased particulate loading to vent filters.	Potential to pressurize vessel	Spills to cell if vessel overflow cannot cope with fill rate Vents potential radioactive and flammable gas into process cell
Impact on Safety Features Provided to Protect Against other Hazards	Difficulty in maintaining adequate vessel depression because of separate inert gas containment requirements. (See Ease of Justification)	Difficulty in maintaining adequate vessel depression through air bleed inlets (i.e., impacts fan capacity)	Difficulty in maintaining adequate vessel depression through air purge inlets (i.e., impacts fan capacity)	Difficulty in maintaining adequate vessel depression through air bleed inlets (i.e., requires greater fan capacity)
Impact of other Hazards upon the Control Strategy Element	Common-cause internal events (e.g., fire, flooding) may disable equipment	Potential vessel overfill may disable system by blocking inlets Common-cause internal events (e.g., fire, flooding) may disable equipment	Common-cause internal events (e.g., fire, flooding) may disable equipment	Potential vessel overfill may disable system by blocking inlets
Robustness to other Fault Conditions and Environments	Designing system to meet seismic requirements would be costly Vulnerable to events resulting in loss of power	Designing system to meet seismic requirements would be costly Vulnerable to events resulting in loss of power	Designing system to meet seismic requirements would be costly Vulnerable to events resulting in loss of power	No significant impact noted. Relatively simple to design to meet seismic requirements
Passive or Active	Active	Active	Active	Passive
Robustness of any Administrative Controls Required	Acceptable - no onerous or unproven requirements known	Acceptable - no onerous or unproven requirements known	Acceptable - no onerous or unproven requirements known	Acceptable - no onerous or unproven requirements known

Table 3.1-10. Hydrogen Hazard Engineering Evaluation

Criterion	Inert Vapor Space	Active Vessel Ventilation (Bleed-In Air Supply)	Active Air Purge & Exhaust	Passive Vessel Vent
Cost	Most expensive option; requires separate gas handling equipment, high consumption rate of inert gas likely (see Ease of Justification)	Acceptable - this is the baseline system	Acceptable - this system would likely cost less than the inerting option	Acceptable - relatively low cost due to simplicity of option Monitoring and provisions to ensure vents cannot block may be required
Operability	Well proven in certain applications	Well proven	Well Proven	System is fully passive; no operator action required
Maintainability	Well proven	Well proven	Well Proven	System does not require maintenance
Ease of Justification	May be ineffective[1] in this application.	Proven Technology	Proven Technology	Proven Technology; however requires detailed, case-by-case justification

1 Since radiolysis of water continually produces both hydrogen and oxygen gas, injecting an inert gas such as nitrogen, by itself, may be ineffective in preventing the buildup of explosive concentrations in the vessel vapor space. In vessels that contain chemical compounds, hydrogen production dominates because of reactions such as corrosion. (This seems unlikely for the TWRS-P HLW storage vessels, since the contained solids are already oxidized. See Section 3.1.2.1.1.) Also, oxygen release from the liquor can be significantly reduced as it is absorbed by these compounds. Either effect is sufficient to allow inerting to be successful, as has been demonstrated in UK practice. If such a demonstration cannot be supported for the TWR-S HLW storage vessels, inerting would have to be conducted simultaneously with another control strategy such as forced air purge and exhaust. Both control strategies might have to remain operable following a prolonged loss of AC power and be seismically qualified. Furthermore, an inerting control strategy in combination with forced air purge and exhaust would require either continuous injection of the inert gas or a gas recovery system, which is anticipated to be relatively complex and expensive.

The main potential benefit from inerting would therefore be to lengthen the time required to reach flammable conditions. With the vapor space initially inerted, flammability would be governed by buildup of the oxygen concentration. Since one mole of oxygen is produced by radiolysis for every two moles of hydrogen, as it takes twice as long for oxygen to buildup to a given volumetric concentration than for hydrogen. Furthermore, hydrogen is not flammable until the oxygen concentration exceeds 5 vol%. (NRC 1978)

Commercial BWR nuclear power plants having Mark I and II primary containments are inerted during normal operation, when no hydrogen generation is occurring. These plants are required also to have redundant, safety-related hydrogen recombiners to control the production of hydrogen following a loss of coolant accident. As noted above, the purpose of inerting is simply to "buy" time; ultimate control of hydrogen is accomplished by the recombiners. The associated operating procedures require the operator to turn on a recombiner when oxygen concentration reaches approximately 4.5 vol%.

The controls analyzed above are all proven controls and have been successfully implemented by BNFL. Since the target frequency for the unmitigated consequences estimated for a detonation of hydrogen accumulated in an HLW storage vessel is 10^{-6}, the control strategy will need to incorporate multiple independent elements. Therefore, it is necessary to consider the compatibility of the proposed controls.

The function of the inerting option is exclude air from the vessel vapor space. The function of the forced air purge and the air inbleed is to circulate air through the tank vapor space to reduce hydrogen concentrations. Therefore, the inerting option is incompatible with the air purge option and the active ventilation option. It is not practical to combine the inerting option with the passive vent option, because the passive vent system connects to the process cell. Where inerting has been applied in the UK on a large nuclear facility, it has been necessary to provide separate ventilation extract systems when large throughputs are required (on the order of 1,000 cfm or 1,700 m^3/hr). This is because the handling properties of pure N_2 are quite different from those of air at such throughputs.

Under normal operating conditions, the forced purge option adds air to the vessel vapor space. There also needs to be airflow through the passive vent openings. Therefore, these two options are not compatible.

The combination of the active vessel ventilation system and a passive vessel vent is particularly attractive because of its inherent safety characteristics. The active vessel ventilation system can be designed to provide sufficient flow through the passive vent openings to maintain the confinement function of the vessel. The passive vent system functions automatically upon loss of the vessel ventilation system and can be designed to function indefinitely without operator intervention. This feature means that, unlike active systems, the passive vessel ventilation system would require no operator attention after severe natural phenomena events, such as an earthquake. Active systems will require long-term action to refuel diesel generators or to restore off-site power.

Forced air purge in combination with the active ventilation system is a proven means of effectively controlling hydrogen. This combination could be designed so that it would not be necessary to provide openings between the cell and the vessel vapor space. However, it would be more difficult to achieve the SL-1 frequency target with this combination than with the PVVS/passive vent combination for the following reasons:

- The combination is more susceptible to common mode failures (for example, loss of power) than the passive vent/vessel ventilation combination.
- The air purge and the vessel ventilation system would not be truly independent because they share a common vent path.

3.1.3.2.3. Control Strategy Selected

The combination of the active vessel ventilation system and the passive vessel vent is selected as the preferred control strategy for this example on the basis of cost, the preference for passive features, and consideration of defense in depth. The selected control strategy is illustrated in Figure 3.1-2. In addition, although not credited in the control strategy, design and operational provisions will be taken to minimize potential sources of ignition.

It should be noted that this choice needs to be reconsidered once all of the hydrogen sources in TWRS-P have been quantified so that the full impact on the vessel ventilation system can be assessed. Based on preliminary estimates, 10 to 12 vessels may require passive venting. An early assessment indicates that the complex of plant ventilation systems can accommodate passive venting. The increased flowrate in the PVVS would be compensated, in part, by a decreased flow requirement on the C5 Extract (cell exhaust system). However, further study of other PVVS system parameters –e.g., system pressure drop, etc. – must be conducted before an integrated determination of the overall viability of passive vessel venting can be made for the TWRS-P project.

3.1.3.3. Structures, Systems, and Components that Implement the Control Strategy

The following SSCs are required to enable the PVVS to fulfill its Important to Safety (ITS) function:

- Engineered air inlets sized and spaced to ensure adequate dilution of hydrogen in the vessel vapor space (**Safety Function**).

- Ducting to provide a reliable air flow path from the vessel to the building exhaust (**Safety Function**).

- Fans to provide a motive force to pull dilution air into the vessel and exhaust the air from the building (**Safety Function**).

- Instrumentation and control (I&C) to monitor ventilation flow rate and initiate corrective action if the flow rate falls below minimum acceptable (**Safety Function**). Systems that support the ITS I&C systems (e.g., power supply, instrument air, etc.) must themselves be classified as important to safety.

- Electrical power supply system.

The following SSCs are required to enable the Passive Vessel Vent to fulfill its Important to Safety function:

- Storage vessel with engineered air inlets and outlet(s) sized and spaced to assure adequate dilution of hydrogen in the vessel vapor space (**Safety Function**).

The following SSCs are required to enable the Passive Cell Vent Path to fulfill its Important to Safety function:

- Seismically qualified ducting, locked open inlet damper (**Operational Assumption**) and backflow filter to provide a passive vent path from the cell (**Safety Function**).

- Cell structure seismically qualified to protect the vent path (**Safety Function**).

- Out-of-cell structures and components designed as “seismic 2 over 1” as necessary to protect the vent path (**Safety Function**).

As noted previously, the need to address potential episodic releases of hydrogen is an **Open Issue**. One possible mechanism for producing such a release is prolonged shutdown followed by restart of the pulsejet agitation system. Resolution of the open issue may reveal the need to classify portions of the agitation system as ITS.

3.1.4. Safety Standards and Requirements

3.1.4.1. Reliability Targets

Because the hydrogen explosive hazard is a Severity Level 1 event for facility and co-located workers, the overall reliability target with respect to those populations for the selected control strategy is $\leq 10^{-6}$ per year. Credit is taken only for the active PVVS and the passive vessel and cell vents in assessing whether this target reliability has been met. For purposes of selecting safety standards and requirements, this overall reliability target is apportioned as follows:

- Active PVVS -- $<10^{-2}$/yr failure rate[h]
- Passive Vessel and Cell Vents -- $<10^{-4}$ probability of failure on demand

3.1.4.2. Performance Requirements

The performance requirements for the SSCs comprising the selected control strategy are as follows:

1. Active Process Vessel Ventilation System

    - Maintain the hydrogen concentration in the HLW Storage Vessel vapor space ≤ 1 vol% (**Safety Function**) under conditions that would produce the maximum hydrogen generation rate from any HLW storage vessel (**Design Assumption**)

    - Provide sufficient flow to maintain confinement. (**Safety Function**)

2. Passive Vessel Vents

    - With active vessel ventilation inoperable, maintain the hydrogen concentration in the HLW Storage Vessel vapor space ≤ 4 vol% (**Safety Function**).

    - Maintain functionality under all anticipated conditions. The only conditions that present a challenge to passive venting are:

        - Vessel overfilling and potential vent plugging and
        - Seismic loading (**Design Assumption**).

        The passive vessel vent must be designed to remain functional under these conditions.

3. Storage Vessel

    - Maintain configuration during and following an earthquake to ensure that the passive vents will perform as designed (**Safety Function**).

    - Provide means of precluding blockage of both active and passive vent systems. **Safety Function**.

[h] A failure rate of much less than 10^{-2}/yr for the PVVS is highly desirable to minimize usage of passive venting, which could lead to spread of radioactivity.

4. Cell

- Protect the active and passive ventilation components from the effects of natural phenomena hazards and external man-made events (**Safety Function)**.

5. Passive Cell Vent Path

- With active vessel ventilation inoperable, maintain hydrogen concentration in the HLW vessel vapor space ≤ 4 vol% during passive venting (**Safety Function**). This concentration is well below that required to produce a significant overpressure, assuming ignition occurs.

- Filtered to minimize the spread of radioactivity outside cell.

- Remain operable during and following an earthquake (**Safety Function**).

Note: If both the process vessel ventilation and the cell ventilation (i.e., C5 extract) systems are inoperable, hydrogen vented via the vessel system passive vent will begin to accumulate in the cell. The time to reach the lower flammability limit of 4 vol% hydrogen in the smaller of the two associated process cells is determined in Lindquist 1999a. This duration is based on the combined hydrogen generation rate from vessels V31001C, V31001D, and V31001E, conservatively assuming no outflow from the cell. Vessel V31001C is assumed to be 83.5% full (overflow volume) of washed solids from Hanford tank 241-AZ-101. The remainder of the 390 m^3 (103,000 gal) of the contents of tank AZ-101 is assumed to be contained in vessel V31001D. Vessel V31001E is assumed to be 83.5% full of washed solids from Hanford tank 241-AZ-102. Although BNFL Inc. does not anticipate that TWRS-P will store HLW washed solids in this configuration (see Section 3.1.1.1.1), this set of assumptions is bounding for the purpose of determining buildup of hydrogen in an HLW process cell.

The calculated time to LFL in the cell is approximately 26 days.[i] This time is sufficiently long that manual intervention could be relied on to establish the cell vent path, which would then reduce the hydrogen concentration in the cell. However, the selected control strategy is to maintain the cell vent path normally open; no manual intervention will be required to activate passive cell venting. Any damper(s) in the cell vent path will be locked open. (**Operational Assumption)**.

[i] This duration is based on an assumption of perfect mixing between the vessel vapor space and cell. In reality, there will be a slight gradient of the H_2 concentration between the vapor space and cell. Any perceived nonconservatism in this assumption is more than compensated by other conservatisms in the analysis. (For example, the calculated cell free volume conservatively ignores the combined vapor spaces of the three vessels.)

6. Out of Cell Structures and Components

   - Protect the passive cell vent path from the effects of natural phenomena hazards and external man-made events. (**Safety Function)**.

3.1.4.3. Administrative Measures

The administrative measures required to assure the selected control strategy are as follows:

Normal Operations

Normal operations will be conducted in accordance with approved operational safety requirements and in strict accordance with administrative and procedural control. Operators will be trained and assessed on the conduct of normal operations. Operational procedures, routine schedules and records will augment training.

Arrangements for the examination, inspection, maintenance and testing of all ITS equipment will be managed through a plant maintenance schedule (PMS). All maintenance activities will be carried out using appropriate maintenance instructions.

Administrative measures that are required for normal operations and are specific to control of hydrogen in the HLW storage vessels are as follows:

- Procedures associated with ventilation control.

- Maintenance and testing requirements for the active Process Vessel Ventilation System to ensure that the reliability targets in Section 3.1.4.1 are met.

- Maintenance and testing requirements for systems that support PVVS (e.g., electrical power, instrumentation and control, etc.)

- Depending on resolution of the **Open Issue** regarding the potential for common cause plugging of passive vessel vent inlets, periodic inspections to verify that the vents are open and unobstructed may be required.

- Routine operating schedule for venting submerged dead legs (unless an automatic means is devised). Records documenting completion of this operation will be made and retained. Such routine activities will be scheduled in an automated prompting system under control of a responsible person.

Operator Response to Abnormal Conditions

Operators will be trained to identify, diagnose and respond to abnormal operating conditions. Plant information will be relayed to the operator in such a manner to aid the operator in performing this duty. Typically, any deviation of the process from its normal operating condition will generate an alarm appropriate to its importance. This alarm will annunciate at the operator workstation or locally within the facility. Operational procedures will detail the:

– Actions the operator must perform to minimize the impact of the abnormality.

- The potential initiators
- The follow up actions required, when plant conditions have been stabilized.

There will be training and operational procedures to ensure the correct responses are carried out by the operators for the following abnormal conditions within HLW storage vessels V31000A, B, C, D and E:

- High level within the vessel. The purpose is to minimize the challenges made to the vessel vent overflow collection system.

- Failure of active vessel ventilation.

- Failure of pulse jet system.

- Startup of pulse jet system following a prolonged loss of vessel agitation (**Open Issue)** related to potential for large, episodic release; see Section 3.1.6.3).

3.1.4.4. Administrative Standards

Operation of the TWRS-P facilities shall be conducted in accordance with proven practices from BNFL operations in the UK and the US. Arrangements will be in place to maintain and demonstrate compliance with all Safety Criteria detailed within the authorization basis.

Administrative arrangements will provide the framework for how facility operations will be conducted for all modes of operation.

The conduct of operation guidelines will be generated by the tailored application of appropriate sections of the following standards:

IAEA 50-C-0, Code on the Safety of Nuclear Power Plants Operation
DOE Order 5480.19, “Conduct of Operations Requirements for DOE Facilities”
DOE Order 4330.4B, “Guidelines for the Conduct of Maintenance at DOE Nuclear Facilities”
Appropriate standards from the Institute for Nuclear Power Operations.

This framework of conduct will be implemented through:

- Management and organizational structure

- Documents, records and certification, including response to abnormal operating conditions, key compliance recording and archiving

- Structured training programs for all personnel, tailored to their roles and responsibility

- Emergency preparedness implemented by having an emergency response structure, training, exercises and procedures

- Incident reporting arrangements

- Safety documentation hierarchy, with appropriate flow down of information into operational documentation. All safety implications will be clearly identifiable within the operational procedures

- Quality assurance

- Arrangements for the examination, inspection, maintenance and testing of all ITS equipment

- Clear labeling of ITS equipment throughout the facility.

3.1.4.5. Design Safety Features

Design safety features needed to implement the proposed control strategy are summarized in Table 3.1-12. More specific information on these design safety features is as follows:

1. Active Vessel Ventilation

   a) Fans

      - Two 100% fans

   b) Instrumentation and controls

      - On detection of low air flow, alarm and initiate automatic switchover to standby fan

   c) Electrical power supply

      - Two separate offsite power feeds

      - Each PVVS fan motor powered from a separate 480 V bus

      - PVVS motor buses backed by emergency diesel generator. To minimize challenges to passive venting, the emergency diesel generator should be capable of starting and loading the PVVS fan within 19 hours of a loss of offsite power based on time for H_2 concentration in HLW vessel to increase from 1 vol% to 4 vol%; see Table 3.1-6. Ideally, however, standby power should be made available to the PVVS fan in as short a time as practicable to minimize spread of radioactivity during passive venting.[j]

2. Passive Vessel Vents

   - One or more outlet pipes at the top of the vessel dome; the location, diameter, and length of the outlet pipe(s) will be analytically determined.

   - Multiple inlet pipes high on the vessel wall; the number, location, diameter and length of the inlets will be analytically determined. The inlet pipes shall be oriented horizontally so as to drain to the process cell in the event of a vessel-flooding event. The total flow area of the inlet pipes

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[j] The final allowable start and load times for the emergency diesel generator will be determined based on an assessment of the design basis requirement of all loads served.

shall be sufficient to prevent blockage of the passive vent inlet openings during a tank overflow (**Design Assumption**).

- Seismically qualified.

3. Storage Vessel

- Seismically qualified
- Provided with sequential high level instrumentation with alarm and trip functions
- Overflow line connection below the passive vent inlets.

4. Passive Cell Vent Path

- Seismically qualified passive vent path to outside the cell.
- Adequate filtration to minimize spread of radioactivity. (**Open Issue**)

5. Cell

- Cell structure seismically qualified.

6. Out of Cell Structures and Components

- Out of cell structures and components whose failure could reduce the functioning of the passive cell vent path to an unacceptable safety level must be designed as "seismic 2 over 1."

3.1.4.6. Design Standards

The designers used these performance requirements to choose the appropriate design standards and consensus codes that are consistent with the reliability targets associated with each system. Their choice was based on professional engineering judgement, combined with industry experience and SRD requirements. Additional detail on the generic design requirements and associated reference consensus standards pertaining to each major discipline area can be found in the Basis of Design (BNFL Inc. 1998a).

The design standard for the HLW storage vessels is ASME Section VIII, Division 1. The passive vent system and the process vessels themselves must be capable of withstanding design basis natural forces events specified in SRD SC4.1-4 (BNFL Inc. 1998c). The passive vessel vent inlet pipes and their supports will be designed in accordance with ASME B31.3, Process Piping, rules for Category M fluid service.

HVAC components in the process vessel ventilation system will be designed in accordance the following:

Fans	ASME AG-1	Code on Nuclear Air and Gas Treatment Section, Section BA
HEPA Filter	ASME AG-1	Code on Nuclear Air and Gas Treatment Section, Section FC
Filter Frames	ASME AG-1	Code on Nuclear Air and Gas Treatment Section, Section FG
Ductwork	ASME AG-1	Code on Nuclear Air and Gas Treatment Section, Section SA
	ASME N509*	Nuclear Power Plant Air-Cleaning Units and Components
	ASME N510*	Testing of Nuclear Air Cleaning Systems
Vent piping downstream of scrubber C6100	ASME A312	Standard Specification for Seamless and Welded Austentic Stainless Steel Pipes

*WAC 246-247 references these codes and standards. ASME AG-1 specifies the requirements for design, fabrication, inspection, and testing of air cleaning and conditioning components and appurtenances, as well as air cleaning components used in engineered safety systems in nuclear facilities. AG-1 was developed by nuclear steam supply system suppliers, operating owners, architects/engineers, members of the Nuclear Regulatory Commission, various manufacturers and individuals with general interest.

The cell structure protects the process vessel, and the superstructure surrounding the cells protects the passive cell vent path during a natural phenomena hazard (NPH) event. The ventilation of the tank and tank integrity are required to be maintained during and following an earthquake. The cell structure is also required to maintain confinement of the hazard associated with hydrogen generation during the event.

In order to meet these performance requirements, the structure is categorized as PC-3, in accordance with DOE-STD-1021, *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components.* The NPH event loads will be determined in accordance with the following codes and standards:

- DOE-STD-1020, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities”
- ASCE 4, “Seismic Analysis of Safety-Related Nuclear Structures and Commentary”
- ASCE 7, “Minimum Design Loads for Buildings and Other Structures”

The following standards have been selected for design of the structural steel and concrete to ensure that the confinement barriers will bot be compromised. These standards provide more conservative design allowable and prescribe more conservative design methods than those provided by model building codes. The structural elements resulting from designing with these standards will provide a robust structure, which will withstand the natural phenomena hazards.

- ANSI N690, “Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures for Nuclear Facilities”

- ACI 349, “Code Requirements for Nuclear Safety Related Concrete Structures”.

Based on the robust configuration of both the onsite and offsite electrical power supply systems (see Category 1 section 2.5), the target reliability of the active vessel ventilation system is readily attainable using the industrial electrical standards listed below. These standards pertain to the electrical components (e.g., switchgear, motor control centers, wiring, etc.) necessary to provide reliable electric power to the PVVS fan motors, control systems and instrumentation and are consistent with the design safety features described in Table 3.1-12.

- IEEE-141, Recommended Practice for Electric Power Distribution for Industrial Plants

- IEEE-142, Recommended Practice for Grounding of Industrial and Commercial Power Systems

- IEEE-446, Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications

- IEEE-493, Recommended Practice for Design of Reliable Industrial and Commercial Systems

- ANSI/IEEE-C37, Circuit Breakers, Switchgear, Substation, and Fuses

- ANSI/IEEE-C57, Distribution, Power, and Regulating Transformers

- NFPA-69, Standard on Explosion Prevention Systems[k]

- NFPA-70, National Electrical Code

- NFPA-497, Recommended Practice for Classification of Hazardous Locations for Electrical Installations in Chemical Process Areas

- NEMA-250, Enclosures for Electrical Equipment (1000 V maximum)

- NEMA-MGI, Motors and Generators

[k] NFPA 69 applies to systems and equipment used for the prevention of explosions and for the prevention or control of deflagrations (NFPA 69, section 1-1.1) in combustion processes, such as furnaces (section 1-1.2(d)). Since, in this example, hydrogen is generated at by radiolysis and not combustion, the standard does not apply. However, since NFPA 69 represents best industry practice, BNFL Inc. will adopt the standard in a tailored fashion.
For the hydrogen hazard in the HLW storage vessels, the following sections of NFPA 69 are relevant:
3-3.1 *The combustible concentration shall be maintained at or below 25% of the LFL.* BNFL Inc. adopts this section for the active vessel ventilation system.
3-3.1 – *Exception No 1* *When automatic instrumentation with safety interlocks is provided, the combustible concentration shall be permitted to be maintained at or below 60% of the LFL.* A reasonable interpretation of this section is that it applies to automatic instrumentation is designed to shut down combustion processes such as furnaces. It is impossible to “shut down” radiolysis, therefore, BNFL Inc. does not adopt this Exception.
3-4.1 *Instrumentation shall be provided to monitor the control of the concentration of combustible components.* BNFL Inc. interprets this section as requiring either direct monitoring of hydrogen concentration or monitoring of air flow that dilutes the hydrogen and from which its concentration can be inferred.

- NEMA-WC, Wire and Cable Standards
- NEMA-ICS 1, Industrial Control and Systems General Requirements
- 29 CFR 1910 Subpart S, Occupational Safety and Health Standards, Electrical

The SRD Implementing Codes and Standards listed for the safety criteria related to the electrical power supply system are beyond the requirements of this example; therefore, they are not identified here. Subsequent hazard evaluations may identify more stringent requirements that cannot be met with the design standards and robust industrial electrical system described herein. If higher demands are placed on the electrical supply system by subsequent hazard evaluations, the electrical system standards and possibly the configuration of the electrical supply system will be adjusted accordingly.

In the case of instrumentation and control requirements and design standards, the specifications are identified on a component-by-component basis in concert with development of the P&ID for the vessel ventilation system. Instrumentation can be expected to include, for example, run status indication of fans or compressors, valves and dampers position indication, and the seal pots status (full or empty) needed to assure an open ventilation path. Specific consensus standards for instrumentation will be specified along with the instrument. Specifications for a typical flow-measuring device that could be used to monitor the vessel ventilation system are shown (BNFL Inc. 1999). Instrumentation in contact with the interior of the ventilation duct will be designed for use in potentially explosive atmospheres as specified in NFPA 70, NEC Article 500. Reliability of the instrumentation will be commensurate with the overall system reliability target (failure rate less than 1×10^{-2} per year). The requirements of ISA S84.01, "Application of Safety Instrumented Systems for the Process Industries" will be followed when designing the instrumentation for the vessel ventilation system. For example, fault tree analysis will be used to determine the appropriate Safety Importance Level (SIL) for the instrumentation used to detect and alarm low flow conditions. If a SIL greater than SIL-1 is indicated, reliability would be achieved by use of redundant/diverse systems such as thermal flow detection supplemented by differential pressure measurements.

3.1.4.6.1. Standards not in the SRD

The standards listed in the previous subsection are those identified in accordance with the integrated safety management process of DOE/RL-96-0004 (DOE/RL 1998a). Of the standards identified above, the following are not contained in the SRD:

- ASME AG-1
- ASTM A312
- ANSI N690
- IEEE-141
- IEEE-142
- IEEE-446
- IEEE-493
- ANSI/IEEE-C37
- ANSI/IEEE-C57
- NFPA-69
- NFPA-497

- NEMA-250
- NEMA-MGI
- NEMA-WC
- NEMA-ICS 1
- 29 CFR 1910 Subpart S

3.1.5. Control Strategy Assessment

3.1.5.1. Performance Against Common Cause and Common Mode Effects, and Design Basis Events

The control strategy must be designed to remain functional following any natural phenomena hazards (NPH) and internally generated common cause hazards that may affect the facility. Internal common cause hazards include events such as fires and internal flooding. Other internal design basis events identified by the ongoing safety analysis that could affect the strategy must also be shown incapable of compromising the ability of the strategy to control hydrogen hazard in the vessels.

3.1.5.1.1. Natural Phenomena Hazards

The design basis natural forces and external events pertinent to these systems are specified in the SRD and ISAR and include seismic events, high wind, wind missile, flooding, snowfall, aircraft impact, and volcanic ash. With the exception of the seismic event, it is expected the facility structure will provide adequate protection against these events (see Section 2.10). The preferred control strategy is selected partly based on its resilience against common cause failures.

Since the vessels will continue to generate hydrogen following a design basis earthquake, the control strategy selected for this example requires that the passive vessel vent and passive cell vent be seismically qualified. Also, out-of-cell structures and components must be designed and constructed so that an earthquake will not cause failure that could reduce the functioning of the passive cell vent to an unacceptable safety level (i.e., “seismic 2 over 1”).

3.1.5.1.2. Internal Common Cause Hazards

Ultimately, the chosen control strategies must be shown to be tolerant to internally generated, common cause hazards that include, but are not limited to, loss of electrical power, fire, and internal flooding. The control strategy – which includes the passive vessel vent – was selected partly because loss of electrical power will not disable the passive vent. The design will provide adequate separation of redundant equipment (i.e., the PVVS active components) to ensure that a credible fire or internal flood will not result in loss of the capability to dilute the hydrogen. Internal common cause hazards will be examined in detail during the remainder of the design activity.

For the selected control strategy, a potential common cause failure mechanism is plugging of the active and passive vessel vent inlets due to inadvertent overfilling the vessel or accretion of airborne particles on the inlet piping internal surface. **(Open Issue)**

3.1.5.2. Comparison with Top-Level Principles

The selected control strategy has been evaluated against a set of relevant top level radiological, nuclear and process safety standards and principles (DOE/RL 1998b), as set forth below.

3.1.5.2.1. Defense in Depth (DOE/RL-96-0006, 4.1.1)

Defense in depth is one of the general radiological and nuclear safety principles in DOE/RL-96-0006. SRD Volume II, Appendix B contains the BNFL *Implementing Standard for Defense in Depth*. This Implementing Standard governs application of the defense in depth principle on the TWRS-P project.

To satisfy the application of defense in depth, the elements of the control strategy must ensure "…that no one level of protection is completely relied upon to ensure safe operation. This safety strategy provides multiple levels of protection to prevent or mitigate an unintended release of radioactive material to the environment." (BNFL Inc., 1998c).

DOE/RL-96-0006 formulates the defense-in-depth principle in terms of the following six sub-principles:

- Defense in depth
- Prevention
- Control
- Mitigation
- Automatic Systems
- Human Aspects

The following paragraphs discuss the application of each of the Implementing Standard to the selected control strategy for the hydrogen hazard in the HLW storage vessels:

1. Defense in Depth (DOE/RL-96-0006,4.1.1.1)

DOE/RL-96-0006, Section 4.1.1.1, requires the following:

> *"To compensate for potential human and mechanical failures, a defense-in-depth strategy should be applied to the facility commensurate with the hazards such that assured safety is vested in multiple, independent safety provisions, not one of which is to be relied upon excessively to protect the public, the workers or the environment. This strategy should be applied to the design and operation of the facility."*

Section 3.0 of the BNFL Inc. *Implementing Standard for Defense in Depth* addresses the defense in depth subprinciple specifically. For an SL-1 event, section 3.0 of the Implementing Standard requires:

- Two or more independent physical barriers to confine the hazardous (i.e., radioactive) material
- Application of the single failure criterion
- A target frequency of <1 x 10^{-6}/y for the SL-1 consequences.

Assessment

Generation of radiolytic hydrogen in the HLW storage vessels has the potential to result in SL-1 consequences to the facility worker and the co-located worker. For potential SL-1 consequences, the *Implementing Standard for Defense in Depth* requires a minimum of two independent physical barriers. It also requires that the single failure criterion shall be applied to the control strategy.

The TWRS-P design provides two physical barriers against the release of radioactivity from the HLW storage vessels. The first barrier to release consists of the vessels and the PVVS; the second barrier consists of the process cells and the C5 ventilation system.

The evaluation of the hydrogen hazard indicates that an event energetic enough to compromise both confinement barriers cannot be ruled out at this at this stage of the design. Therefore, the control strategy applied to the hydrogen hazard in the HLW storage vessel is to preclude buildup of radiolytic hydrogen. This strategy is implemented by providing two independent and diverse means of removing hydrogen from the vessels. The primary means of removing hydrogen from the HLW storage vessels is through the PVVS; the secondary means of hydrogen removal is through a passive system that ventilates both the vessel vapor space and the cell.

The reliability target established for the PVVS is readily attainable. Section 3.1.5.4 evaluates the reliability of the PVVS considering the administrative controls that will govern maintenance and surveillance of the system. This evaluation concludes that the target reliability will be met with margin. Therefore, the hydrogen control strategy for the HLW storage vessels does not rely excessively on the PVVS.

The target probability of failure of the passive vent system on demand is also readily attainable. Because of its passive nature, the probability of failure of the passive vent system on demand is a function of the confidence in how it is engineered and constructed. The design of the passive vent system will be based on a modeling methodology that has been validated by experiment. BNFL has a large degree of confidence in the predictions of this methodology. This confidence is based on experimental validation of the methodology and on successful implementation of similar designs in plants in the UK. Additional confidence is provided by applying the highest level of quality assurance to the design and installation of the passive vent system and by implementing a commissioning plan to verify that the passive vent system is properly installed. Therefore, the hydrogen control strategy for the HLW storage vessels does not rely excessively on the passive vent system.

Given the control strategy for hydrogen generation in the HLW storage vessels, the initiating event for hydrogen buildup is loss of the active PVVS. The passive vent system provides protection against this initiator. Therefore, there are no short-term failures. The long-term passive failure is a mechanistic failure, that is, a failure caused by a credible mechanism. Because the passive vessel and cell vents are simple – consisting of short lengths of pipe and a small filter, no such mechanism has been identified. Therefore, the control strategy satisfies the single failure criterion.

Two potential failure mechanisms arising in interfacing systems have been identified as having the potential for rendering passive venting ineffective:

- loss of agitation
- overcooling of the HLW vessel.

Loss of agitation is an issue requiring further resolution (**Open Issue**; see Section 3.1.6.3). BNFL plc has conducted development work for the EP2 plant at Sellafield to evaluate the impact of excess vessel cooling on operability of the passive vessel vent. The relevant knowledge obtained from that development work is discussed below.

A zero thermal gradient will produce “positive” (i.e., upward) flow due to hydrogen buoyancy alone. The passive vessel vent system will be designed to maintain hydrogen concentration well below 4 vol% in the absence of a thermal gradient, assuming hydrogen is not recycled into the vessel vapor space (i.e., hydrogen is not allowed to build up in the cell). When the vessel vapor space is warmer than the cell air, the thermal gradient enhances the buoyant flow induced by the hydrogen/air mixture.

If overcooling of the vessel liquor occurs, the temperature of the gas in the vessel vapor space may drop below the cell ambient temperature. The magnitude of the positive flow will reduce, and, at some point, will reverse. If the temperature drop is sufficient, the reversed airflow will maintain the hydrogen concentrations in the vessel vapor space below 4 vol%.

Assuming that the air flow into the vessel is zero or near-zero and the hydrogen concentration is initially 1 vol%, then, after approximately 20 hours, the concentration may be postulated to exceed 4 vol%. In reality, for this to occur, a stringent set of time-dependent conditions must be concurrently-maintained for the duration: the rate of increase of mixture density due to falling temperature must be countered by the rate of decrease of mixture density due to the evolution of hydrogen. It has been demonstrated that, under such conditions, the system is extremely unstable; therefore, small deviations from these conditions will induce sufficient flow to maintain concentrations below 4 vol% (**Design Assumption**).

The TWRS-P HLW Storage Vessels will be analyzed to demonstrate that the probability of stagnation conditions being maintained for a prolonged period is negligible (**Open Issue**; see Section 3.1.6.3). Within that time frame, the hydrogen concentration in the vessel vapor space and cell would not reach the LFL of 4 vol%.

The remaining five sub-principles of defense in depth are addressed below.

2. Prevention (4.1.1.2)

The control strategy applied to the hydrogen hazard in the HLW storage vessel is to preclude buildup of flammable concentrations of hydrogen. As such, this strategy prevents the production of radiolytic hydrogen in the HLW storage tanks from becoming a credible hazard.

Although not credited in the control strategy, provisions to minimize potential ignition sources will be made for defense in depth.

As shown above, the features used to implement the control strategy are consistent with the requirements in Section 3.0 of the *Implementing Standard for Defense in Depth*.

3. Control (4.1.1.3)

The control strategy for hydrogen generation in the HLW storage vessels maintains hydrogen concentrations well below the LFL. The control strategy, which will be based on the maximum hydrogen generation rate in the storage vessels, will be designed to cope with any episodic releases that could exceed this maximum generation rate.

The control strategy for hydrogen generation in the HLW storage vessels will incorporate means for warning of reduced margins of safety. Currently, the design relies on flow measurements to provide indications that the PVVS and/or passive vent systems are functional. In this case, loss of flow through the vessel vapor space to the PVVS would indicate a reduction in the margin of safety. An alternative method under consideration would be the direct measurement of hydrogen concentration in the vessel vapor space and the cell. In this case, increasing hydrogen concentrations would indicate a reduction in the margin of safety. **Open Issue** (see Section 3.1.6.2).

The HLW vessels will be provided with successive high-level alarms and trips to minimize the potential for challenges to the overflow collection system.

The passive vent system functions automatically upon loss of the PVVS to maintain the HLW vessels and cells in a safe condition.

Although the selected control strategy is very tolerant to system and human failures, administrative controls have been proposed (see Section 3.1.4.3).

4. Mitigation (4.1.1.4)

The TWRS-P design provides a conservatively designed confinement system for the material in the HLW storage vessels. Paragraph #1 above on the defense in depth sub-principle describes this confinement system. The control strategy for hydrogen prevents the generation of radiolytic hydrogen in the HLW storage vessels from developing into a credible hazard. Therefore, hydrogen generation in the HLW vessels poses no challenge to the confinement system.

5. Automation Systems (4.1.1.5)

The active PVVS is a normally operating system; therefore, no automatic signals are required for initiation of the normally operating fan.

The control strategy provides for the following two automatic system responses: (1) switchover from running to standby PVVS fan upon detection of low flow and (2) standby AC power supply to the PVVS.

The passive vent system functions automatically upon loss of the PVVS to maintain the HLW vessels and cells in a safe condition. There is no requirement for operator action or automatic systems.

6. Human Aspects (4.1.1.6)

The active PVVS system is a reliable filtered exhaust ventilation system that is simple to operate and maintain. The passive vessel vent and cell vent are very simple and contain no moving parts; neither requires any operator action. Therefore, this control strategy will not impose an onerous burden on the operators.

The human aspects associated with hydrogen control in the HLW storage vessels will be executed within the project procedures for training, qualification, and quality assurance.

Since the Severity Level for the HLW vessel hydrogen hazard is SL-1, per Section 2.6.2 of the *Implementing Standard for Defense in Depth*, the control strategy must be reviewed against the human factors engineering criteria in IEEE Std. 1023-1988 6.1.1, as tailored by the *Implementing Standard*. This requirement is not addressed in this report, because the PVVS is a conventional filtered-exhaust ventilation system, for which no complicated human factors issues are anticipated. The passive vent does not require operator action.

The control strategy for hydrogen generation in the HLW storage vessels includes administrative controls (see Section 3.1.4.3). Operating limits (Technical Safety Requirements) have not been developed at this time and are not addressed in the report.

Additional Top-Level Principles applicable to the design phase are presented in the following sub-sections.

3.1.5.2.2. Operating Experience and Safety Research (4.1.2.4)

The adopted methods build on operating experience. (See Section 3.1.1.4.) Further safety research to confirm effectiveness of passive venting of the vessel and cell will be conducted later in the design evolution (**Open Issue**; see Section 3.1.6.3).

3.1.5.2.3. Proven Engineering Practices (4.2.2.1)

Passive and/or active venting are commonly used technologies for hydrogen control at Hanford, Sellafield, and Savannah River. See Section 3.1.1.4 for details of BNFL's relevant experience.

3.1.5.2.4. Common Mode/Common Cause Failure (4.2.2.2)

The aggregate strategy is resistant to common mode and common cause failures. Potential common cause and common mode weaknesses identified for the strategy selected are discussed in Section 3.1.5.1. The analysis will continue as the design detail develops.

3.1.5.2.5. Safety System Design and Qualification (4.2.2.3)

Past industry experience indicates the selected control strategy will perform in the TWRS-P facility service environment. The operating environment of the cell is described in Section 3.1.1.3; the environmental conditions in the cell do not present any unusual challenges to the in-cell components. All electrical components related to the control strategy are located outside the cell in a mild environment. The operating conditions for the SSCs are known and addressed in the design.

3.1.5.2.6. Radiation Protection Features (4.2.3.2)

Operation and maintenance associated with the selected control strategy will not result in undue exposure.

A qualitative ALARA assessment was performed of the ten potential control strategies evaluated in Section 3.1.3; none were judged "ALARA adverse". No aspect of the selected control strategy was determined to be adverse to the ALARA objective (Pisarcik 1999).

3.1.5.2.7. Deactivation, Decontamination, and Decommissioning (4.2.3.3)

The selected control strategy does not preclude effective deactivation, decontamination, and decommissioning. Operation of the passive vessel vent, should it occur during the facility's operating lifetime, may result in some additional radioactivity being deposited on internal surfaces of the cell. However, the floor and walls up to flood height will be lined, and the walls above flood height probably will be coated[1], thus preventing entrapment of the radioactivity within the cell concrete.

BNFL's cascade ventilation philosophy (described in Category 1) significantly minimizes migration of radioactivity from vessel to cell (i.e., from primary to secondary confinement), as evidenced by the low airborne radioactivity measurements recorded for similar systems in BNFL's operating facilities. While abnormal occurrences have temporarily led to elevated airborne radioactivity in cells, they have not resulted in activity build-up that would preclude controlled access for deactivation and decommissioning.

BNFL has made several entries into C5 areas following vessel washout and deactivation – the most notable being entries to refurbish the high activity fuel dissolver and associated equipment at the Magnox reprocessing plant at Sellafield. After 20 years of operation, no special provisions were required to decontaminate cell walls, which were virtually uncontaminated.

The air velocity through the vessel vapor space during passive venting will be low, such that the liquor surface will essentially remain undisturbed; therefore, the amount of radioactivity that would be entrained in the moving air will be negligible. The passive vent's airflow rate into the cell also will be small. Furthermore, as demonstrated in Section 3.1.5.4, it is unlikely that the passive vent will operate for any significant time during the facility lifetime. Therefore, the potential for additional radioactivity deposition during passive venting should not impose an undue burden on decontamination of the facility.

3.1.5.2.8. Emergency Preparedness - Support Facilities (4.2.4)

The strategy has no foreseeable impact on the control room or emergency response center that may need to be manned after an event.

3.1.5.2.9. Inherent/Passive Safety Characteristics (4.2.5)

The selected control strategy employs a combination of passive venting of the vessel and cell in the event that active vessel ventilation (PVVS) is lost.

3.1.5.2.10. Human Error (4.2.6.1)

Because ultimate reliance is placed on passively venting the vessels and cell, the selected control strategy is highly tolerant of postulated human errors. No operator action is required to initiate or control passive venting.

3.1.5.2.11. Instrumentation and Control Design (4.2.6.2)

Monitoring will be provided to ensure that hydrogen concentrations remain within the limits defined in Section 3.1.4.2; as a minimum, monitoring of PVVS flow or dP will be provided. Inclusion of permanent hydrogen monitoring is an **Open Issue**; see Section 3.1.6.3. The selected control strategy does not impose any additional instrumentation and control requirements on the active vessel ventilation system (PVVS), which is already part of the facility design. No I&C requirements have been identified for the passive vessel or cell vents. The impact, if any, of passive cell venting on radioactive effluent monitoring is an **Open Issue**; see Section 3.1.6.3.

[1] A final decision to apply decontaminable coatings is subject to an integrated ALARA assessment.

3.1.5.2.12. Safety Status (4.2.6.3)

The selected control strategy will not have a significant bearing on the control room safety status display. The active vessel ventilation system (PVVS), which is already part of the facility design; will not be subjected to any additional monitoring requirements by this control strategy, unless it is decided not to include hydrogen monitoring as part of the control strategy (**Open Item**; see Section 3.1.6.3). Depending on that decision, monitoring of the airflow rate from the HLW vessels to the PVVS may take on greater importance. However, since there is already a need for flow monitoring to ensure that the PVVS is maintaining a negative pressure in the vessels, it is unlikely that any new status-monitoring requirements would be imposed for the purposes of hydrogen control.

3.1.5.2.13. Reliability (4.2.7.1)

Reliability targets have been assigned for important to safety SSCs in Section 3.1.4.1. Section 3.1.5.4 demonstrates that the aggregate control strategy is highly reliable.

Based on the conceptual design of the passive vessel vent, common cause plugging of the inlets (see Section 3.1.5.1.2) is unlikely. Accretion of particulates on the inlet pipe internal surface is improbable. Design provisions (i.e., level alarms and trips, vessel overflow and sizing of inlet pipes), as well as administrative measures for filling the vessels, should preclude this common cause. However, further research is needed to confirm to ensure that these provisions do not adversely impact the reliability target for this control strategy. (**Open Issue)**

Should common cause vent plugging be determined to be a concern, additional inspectability features will be proposed.

3.1.5.2.14. Availability, Maintainability, and Inspectability (4.2.7.2)

The active vessel ventilation system (PVVS) is already part of the facility design; no additional availability, maintainability, and inspectability requirements are imposed for hydrogen control. The reliability assessment of the active PVVS (see Section 3.1.5.4) presumes that standard commercial components will be employed in the PVVS; therefore, the control strategy does not need to impose any special availability criteria.

Should common cause vent plugging be determined to be a concern, additional inspectability features will be proposed.

3.1.5.2.15. Pre-Operational Testing (4.2.8)

The control strategy is amenable to pre-operational testing of its elements, and substantial experience of this exists for these elements.

3.1.5.3. Mitigated Consequences

The control strategy does not incorporate mitigation. Therefore, the mitigated consequences of the potential hydrogen explosion are the same as the "unmitigated" consequences shown in Section 3.1.2.3.3.

3.1.5.4. Frequency of Mitigated Event

Fault tree analysis (Kolaczkowski 1999) of the active vessel ventilation system has conservatively estimated the failure frequency of the system, as it is currently designed, to be, at worst, 1.5×10^{-2} per year. Over 90% of this frequency is attributed to a conservative estimate of the likelihood of both fans being inoperable simultaneously for greater than approximately 24 hours. If the effects of the planned maintenance program are taken into account, the failure frequency of the active vessel ventilation system can be expected to be an order of magnitude lower, based on the range of reliability experienced for these types of components, as demonstrated by the reliability data used in Kolaczkowski 1999. Therefore, it is concluded that the frequency of failure of the active vessel ventilation system for longer than approximately 24 hours will be approximately 1.5×10^{-3} per year.[m]

Given that the control strategy requires that the design preclude plugging of the passive vessel vent system, its probability of failure on demand will be less than 10^{-4} per year. Therefore, the failure rate for the aggregate control strategy is well within the target of 10^{-6} per year.

3.1.5.5. Consequences with Failure of the Control Strategy (Including Mitigation)

For this example, the consequences given failure of the control strategy are identical to those provided in Section 3.1.2.3.3.

3.1.5.6. Frequency of Control Strategy Failure

For this event, no release will occur unless the aggregate control strategy fails. This failure is estimated to occur $< 10^{-6}$/y, which meets the target frequency for this event, as summarized in Table 3.1-11.

Table 3.1-11. Summary of Results

Population	Dose (rem)	Severity Level	Frequency of Control Strategy Failure (y^{-1})
Facility Worker	530	SL-1	$<10^{-6}$
Co-located Worker	27	SL-1	$<10^{-6}$
Public	0.04	SL-4	$<10^{-6}$

3.1.6. Conclusions and Open Issues

3.1.6.1. Conclusions

An initial control strategy and set of implementing design standards have been developed in accordance with the process specified in the *Implementing Standard for Safety Standards and Requirements*

[m] As discussed in Section 3.1.2.1.1, if active vessel ventilation is restored within approximately 24 hours, ignoring the passive vent, hydrogen concentrations in the vessel vapor space will not exceed the lower flammability limit. If credit is taken for the passive vessel vent, this time is increased to greater than three weeks (see Section 3.1.4.2). If the passive cell vent is also credited, then the time to reach LFL would be extended indefinitely.

Identification (BNFL Inc. 1998c). The design safety features identified by this process are summarized in Table 3.1-12. This process used the conceptual design material from the Specification 12 TWRS-P project proposal (BNFL Inc. 1998e) as the primary basis. As such, the design and the control strategies and standards will require additional iterations before the final strategy and the complete set of standards can be specified. This iterative approach is consistent with the required process for standards identification.

The selected control strategy consists of a combination of (1) active vessel ventilation exhaust with passive air inbleed and (2) passive venting of the HLW storage vessels to the cell upon failure of the active system, with passive venting of the cell. This strategy is highly reliable. It emphasizes prevention over mitigation and passive over active safety features. Subject to successful resolution of the Open Issues in Section 3.1.6.3, this strategy offers the prospect of an essentially “walk-away” facility from the standpoint of hydrogen control post-seismic.

However, it should be emphasized that this control strategy was devised as an isolated case. BNFL Inc. will reevaluate hydrogen control globally, giving consideration to explosive hazards throughout the TWRS-P facility. This reevaluation may reveal the need to revise the control strategy for hydrogen control in the HLW storage vessels.

The control strategy is summarized in Table 3.1-12. Section 3.1.6.1 describes further assessments that must be performed to achieve a mature control strategy. Section 3.1.6.2 lists the open issues associated with the selected control strategy.

3.1.6.2. Future Assessments

In support of the ongoing design, safety analysis activities undertaken to continue development of control strategies and standards to reduce the risk of hydrogen or other flammable gas events to acceptable levels will include the following:

The control strategy described in this report is generally applicable throughout the facility. However, the strategy must be tailored to the magnitude of the hazard presented by the remaining hydrogen generating vessels.

The design will be evaluated for other hazards and potential additional requirements and standards needed to fully implement the control strategy. This evaluation will include hazards of potential hydrogen pocketing in dead end piping or instrument bodies, for example.

In the iterative process of standard selection, the design teams will assess the potential preventative measures and mitigation strategies for compatibility with other local, area-wide and facility-wide strategies. This will be accomplished during the ongoing safety analysis of the emerging design.

3.1.6.3. Open Issues

Credibility of Detonation Assumption. As discussed in Section 3.1.2.3, the present analysis makes a very conservative assumption that a hydrogen detonation is possible. However, BNFL experience with hydrogen generation in vessels with designs similar to the TWRS-P design indicates that is likely that the geometry of the TWRS-P tanks and piping will not support a transition from deflagration to detonation. Therefore, the unmitigated consequences from potential hydrogen accumulation postulated in this example may be overly conservative. The credibility of a hydrogen detonation in TWRS-P will be reevaluated when the design details of the geometry, dimensions and routing of connected piping and instrumentation are known.

Hydrogen Monitoring Requirements. The strategy to control the hazard presented by hydrogen accumulation in the tank vapor space does not currently rely on hydrogen monitoring for its effectiveness. The system of active and passive vents will be designed to remove hydrogen at its maximum rate of generation under all foreseeable plant conditions. Thus, the strategy is expected to maintain hydrogen concentrations in the vessel vapor space and vent ducting at essentially nondetectable levels. Conventional hydrogen monitors are relatively insensitive detectors, incapable of detecting hydrogen concentrations below approximately 0.04 vol%. However, flow or dP monitors, which immediately detect loss of air flow, will be provided to ensure that the dilution air system (i.e., PVVS) operates properly. These flow/dP detectors will provide alarm and automatic switchover to the standby PVVS fan.

It is recommended that hydrogen monitors be installed in the active vessel vent ducting to verify the effectiveness of the strategy during initial plant operations. There are currently no plans to maintain these monitors over the life of the plant, however, or to list them as items Important to Safety. This approach was taken for the following reasons:

Beyond providing a historical record of the hydrogen concentrations in the ventilation duct, the monitors could contribute to the safety margin of the facility. This contribution would be limited to the ability to detect trends in concentration that would indicate either higher than expected generation rates, or lower than expected dilution rates. The likelihood for detecting such trends is considered extremely remote and therefore may not warrant the design expense and operational burden required to install and maintain hydrogen monitors over the life of the facility. Monitors installed in the vessel ventilation duct would not be effective in accident situations, since the initiating event itself (loss of primary vessel ventilation) would disable them.

- Installation of hydrogen monitors in individual vessel vapor spaces would provide a similar benefit, and could continue to provide information in post accident situations. However, since the protective strategy is designed to provide maximum dilution at all times, the monitors would not be used to trigger additional control measures. Therefore, as with hydrogen monitors in the ducting, the expense and operational burden required to install and maintain hydrogen monitors in the vessel vapor spaces may be unreasonable.

- Cost-benefit studies will be undertaken during design development to quantify the cost of the monitoring options vs. the benefit of increased margins of safety (i.e., decreased risk of hydrogen explosions). If the result of these studies supports addition of hydrogen monitors to the control strategy, they will be included in the design submitted for construction authorization.

<u>Episodic Releases of Hydrogen:</u> If vessel agitation is interrupted, the suspended solids will soon form a dense mass in the bottom of the vessel. Experience at Hanford and Sellafield has shown that, under certain conditions, this can lead to episodic releases of hydrogen from the layer of settled solids. If the release is large enough, it can momentarily overcome the ability of the ventilation system (passive and/or active) to dilute the gas to safe levels. Engineering studies and testing will be conducted during the remaining design activity to determine the gas retention capabilities of TWRS-P sludge. If necessary, a means to control the hazard will be provided, which will function during and following an earthquake.

<u>Passive Vessel Vent Operation:</u> Preliminary scoping analysis of a non-optimized passive vessel vent configuration for the TWRS-P HLW storage vessels shows that, given the following simplifying assumptions, the passive vessel vent will maintain the hydrogen concentration within the vessel vapor space at well below 4 vol%:

- Perfect mixing between the vessel vapor space and the cell atmosphere
- No hydrogen is re-entrained from the cell atmosphere into the passive vessel inlets
- Vessel and cell are isothermal.

Further, detailed analyses will need to be performed to confirm the following:

- Viability of the passive vessel vent, using final configuration parameters
- Impact of the passive vessel vent inlets and outlet on the active PVVS operation
- Thermal effects (i.e., overcooling) on passive vessel vent performance
- Hydrogen buildup in the vessel vapor space due to interaction with cell atmosphere, with and without passive cell venting
- Potential for common cause plugging of vent inlets and outlet(s).

<u>Passive Cell Vent Path</u>: The configuration of the passive cell vent will be determined later in the design process. Analysis to confirm adequate mixing of hydrogen in the cell and outflow from the cell during passive venting will be performed in a manner similar to that described above for the passive vessel vent.

The vent path must be filtered to minimize the spread of radioactivity outside the cell. Design and testing requirements for the cell vent filter will be developed later. The potential impact, if any, of passive cell venting on radioactive effluent monitoring will be addressed in detailed design.

To ensure operability of the passive vessel vent, the vent path from the cell must be seismically qualified to prevent buildup of a flammable concentration of hydrogen after an earthquake. Depending on the design solution selected, the issue of post-seismic access to the facility, as would be required by personnel to effect this vent path, will also be addressed.

In addition to the open issues listed above, various design and operational assumptions are highlighted in the report. Their continuous validity will be monitored through design development.

Table 3.1-12. Control Strategy Summary

Hazard Description: Radiolytic Hydrogen Explosion in V31001A/B/C/D/E				**Initiator:** Presence of Water and Radioisotopes in Vessel	
Selected Control Strategy	**Important-to-Safety SSCs**	**Safety Functions**	**Design Safety Features**	**Design Assumptions**	**Operational Assumptions**
Active Vessel Ventilation (PVVS)		Reliably keep the H_2 concentration in the tank vapor space and the cell below the LFL during normal operations Provide confinement flow	Designed to keep the H_2 concentration ≤ 1 vol% Designed to maintain confinement airflow through vessel openings	Maintains ≤ 1 vol% at the maximum H_2 generation rate in any HLW storage vessel	
	Fans	To provide airflows and pressures required by system safety function	Redundant 100% capacity fans Automatic switchover on low flow		Only one fan will be taken out of service at a time; redundant fan will be verified to be operable
	Instrumentation and controls	To reveal deviations from required flowrate and start up any back up fans etc	Redundant means of detecting loss of flow in the system Automatic switching to backup fans Alarms on loss of flow Controls flow through the vessel vapor space		
	Ducting	Provide reliable flow path from vessel vapor space to building exhaust	Maintain confinement boundary		
	Flow control and abatement devices	Direct flow from the vessel vapor space to the environment	Redundant flow paths or bypass paths provided for active components subject to isolation or blocking Automatic realignment on fan switchgear		
	Vessel inlets	Provide flow path from cell to vessel vapor space	Sized to ensure adequate dilution of hydrogen in vessel vapor space		
	Electrical supply	Supply reliable electric power to system components	Two separate offsite power feeds Each PVVS fan motor powered from a separate 480V bus PVVS fan motor power supplies backed by emergency diesel generator		

Table 3.1-12. Control Strategy Summary

Hazard Description: Radiolytic Hydrogen Explosion in V31001A/B/C/D/E				**Initiator:** Presence of Water and Radioisotopes in Vessel	
Selected Control Strategy	**Important-to-Safety SSCs**	**Safety Functions**	**Design Safety Features**	**Design Assumptions**	**Operational Assumptions**
Passive Vessel Ventilation		Mixes the atmospheres in the vessel vapor space with the cell atmosphere to maintain H_2 concentrations in the vapor space and the cell below the LFL Maintain functionality during and following an earthquake	Passive system Seismically qualified	Conservatively designed using methodologies validated by experiment and successfully implemented in other BNFL plants – high degree of certainty that performance will exceed design basis Sized to assure H_2 concentration remains below LFL for ≥ 1 week, even if cell is not vented Design promotes mixing Flow through vapor space is maintained independent of temperature gradients	
	Vessel Inlets	Provide flow path between the vapor space and the cell	Seismically qualified Sized not to block even if both the vessel level controls and the overflow line fail to prevent an overflow	The total flow area of the inlet pipes shall be sufficient to prevent blockage of the passive vent inlet openings during a tank overflow	
	Chimney	Provide flow path between the vapor space and the cell	Seismically qualified		
	Vessel	Support passive vessel vent path	Seismically qualified No moving parts or electrical connections (to prevent ignition) Overflow line connection below passive vent inlets	Solids are stored at 25 wt% The overflow line connection is at the 235 m^3 (62,100 gal) (84%)	
	Vessel level instrumentation	Prevent vessel over-filling and potential vent inlet blockage	Multiple high level instruments with alarm and trip functions		

Table 3.1-12. Control Strategy Summary

Hazard Description: Radiolytic Hydrogen Explosion in V31001A/B/C/D/E				**Initiator:** Presence of Water and Radioisotopes in Vessel	
Selected Control Strategy	**Important-to-Safety SSCs**	**Safety Functions**	**Design Safety Features**	**Design Assumptions**	**Operational Assumptions**
	In-cell components	Do not interfere with vessel vent path	Seismically qualified as required to protect the passive vessel vent Electrical components in cell, if any, must be designed to be non-sparking	Layout provides clear vent path	
Cell Vent Path		Provide flow path from the cell to the operating gallery	Passive system Seismically qualified	Conservatively designed using methodologies validated by experiment and successfully implemented in other BNFL plants – high degree of certainty that performance will exceed design basis Sized to assure H_2 concentrations in the cell and vapor space remain below LFL indefinitely	
	Cell Ducting	Provide cell vent path	Seismically qualified		
	Inlet damper	Provide cell vent path	Seismically qualified		Locked open
	Backflow filter	Provide cell vent path	Seismically qualified Low resistance filter design		
	Out of cell components	Do not interfere with cell vent path	Seismically qualified as required to protect the cell vent path	Layout provides clear vent path	
	Cell	Assure cell vent path	Seismically qualified	Protects active and passive ventilation components from the effects of natural phenomena hazards and external man-made events	
	Above cell structure	Assure cell vent path	Seismically qualified as required to protect the cell vent path		

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[n] Copies of these references accompany this deliverable.
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Figure 3.1-1. Schematic of Envelope B & D Processing

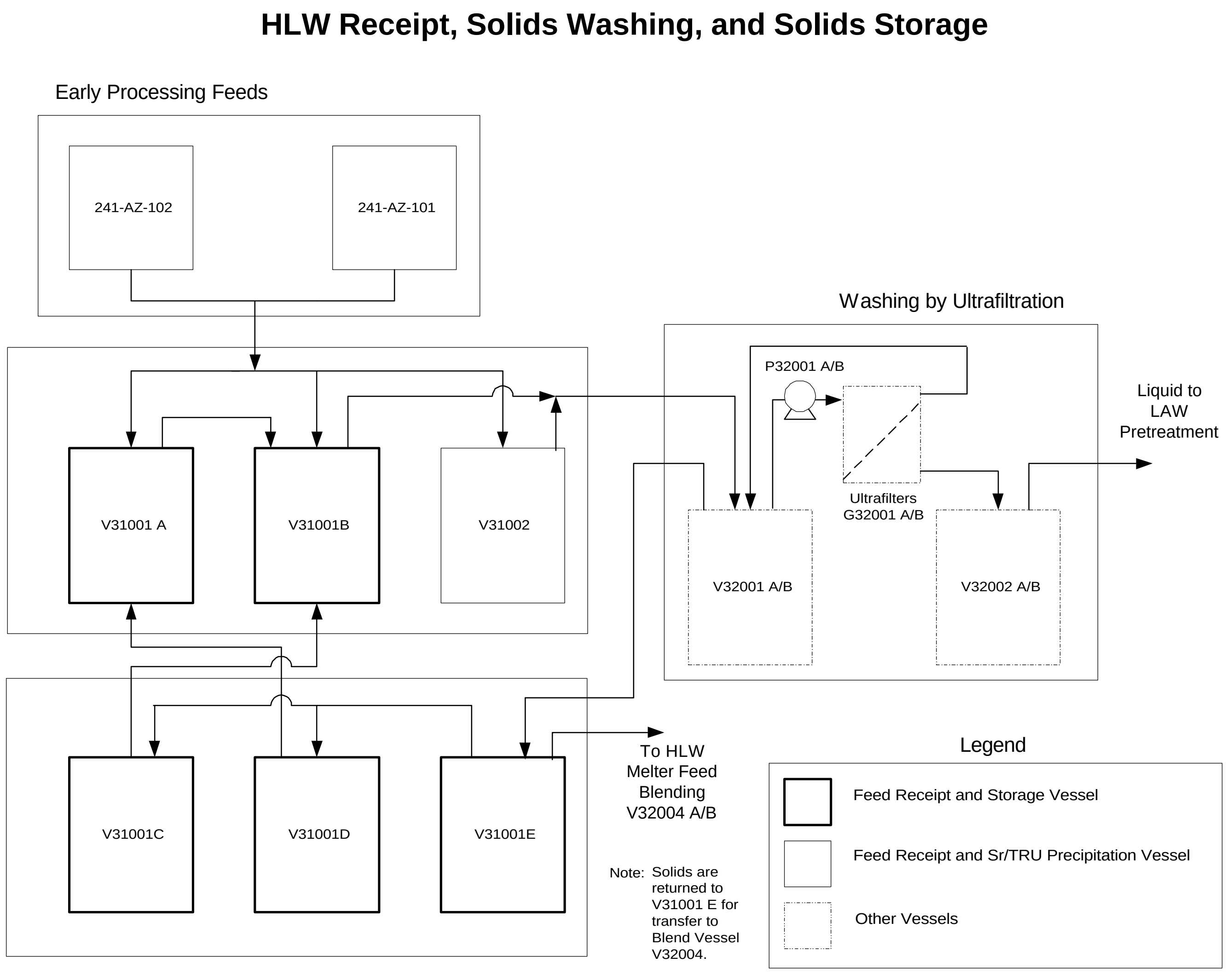

Figure 3.1-2. Control Strategy Schematic